LCA of Passive Smart Windows

A framework for assessing and comparing the environmental impact of Auto-Responsive glazing

Master Thesis Report

Paolo Matricardi

Delft University of Technology

TU Delft

Delft University of Technology

Faculty of Civil Engineering and Geosciences
MSc Building Engineering
Specialisation: Building Technology & Physics

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by

Paolo Matricardi

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Thesis committee:	Prof. dr. ir. P.C. Louter,	TU Delft, Chair
	Dr. A. Luna Navarro,	TU Delft, BK supervisor
	Dr. ir. M. Ottelé,	TU Delft, CEG supervisor

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Abstract

The building sector is increasingly acknowledging the necessity to mitigate its environmental impact in response to the challenges posed by climate change. Adaptive facades specifically are used to develop a dynamic control of the envelope's properties, modifying their behaviour in response to outdoor conditions and indoor stimuli. Thermochromic and photochromic technologies, also known as Passive Smart Windows (PSW) are passive solutions that aim to regulate solar gains through the integration of an Auto-Responsive (AR) layer, particularly for cooling purposes, to reduce energy consumption and minimize the operational impact of buildings.

Existing literature predominantly concentrates on the performance aspects of these technologies, mainly due to their early development stages. However, there remains a gap in assessing the overall environmental impact, both in terms of impact perspective, thus considering several possible effects on the environment, and from a life cycle perspective, thus including both embodied and operational dimensions. The embodied impact, in particular, lacks comprehensive examination beyond considerations of Global Warming Potential (GWP). Furthermore, the dynamic landscape of materials and principles utilized in these technologies adds complexity to their evaluation.

This thesis project aims to bridge these gaps by establishing a comprehensive framework for evaluating the total impact of PSW, encompassing both embodied and operational stages. Through comparative analysis with alternative Dynamic Window Systems (DWS), comprising static windows paired with dynamic shading devices, the framework facilitates a thorough examination. Operational energy calculations are grounded in energy simulations of a standard office space with an exposed facade, while the description of the embodied stages gives an overview of the life cycle of PSW, with focus on different possibilities integrating the AR layer and their consequences.

The application of the framework in a case study reveals nuanced findings. While the GWP of PSW decreases of 1,1%, most of the other impact of PSW increase, including a growth of 0,1% of the Single Score. PSW has a lower impact compared to DWS due to the increased energy demand of the latter but, contrary to the initial expectations, the PSW does not consistently outperform static glazing due to conservative assumptions in energy simulation and a higher replacement rate, which significantly escalates embodied impact. Notably, challenges arise in defining materials for the AR layer, necessitating collaboration with manufacturers to improve data availability.

The study identifies replacement as a critical factor in determining overall impact, underscoring the importance of extending the lifespan of PSW or to consider a detachable layer to enhance its environmental sustainability. However, criticisms regarding the partial nature of the analysis emerge, particularly in neglecting user comfort and control over the facade, as well as the temporal flexibility of the technology. Future research directions should incorporate these aspects for a more comprehensive evaluation.

Ultimately, this thesis emphasizes the interdependency between the LCA approach, the energy simulation and the context of the PSW's application. This highlights that the environmental impact assessment of such building elements can not leave the contextual application out of consideration in order to provide a sufficiently reliable result, thus limiting the use of this framework mainly to defined projects rather than to the estimation of generic impact for a PSW product.

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List of abbreviations

Abbreviation	Definition
AR	Auto-Responsive
DWS	Dynamic Window System
EF3.1	Environmental Footprint LCIA method
Emb	Embodied Impact
EnIC	Enviornmental Impact Category
E-o-L	End-of-Life
EPD	Environmental Product Declaration
ESL	Expected Service Life
FU	Functional Unit
HVAC	Heating, Ventilation and Air Conditioning
IS	Impact Score
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LS	Lifespan
NIR	Near Infra-Red elechtromagnetic band
Op	Operational Impact
PCM	Phase Change Materials
PSW	Passive Smart Window
sol	Solar elechtromagnetic band
StW	Static Window
Tc	Transition or Critical temperature
U	Thermal transmittance
vis	Visible elechtromagnetic band
WWR	Window-to-Wall Ratio
α	Absorbance
ρ	Reflectance
τ	Transmittance

1
Introduction

1.1. Introduction

1.1.1. The role of glazing in the building envelope

The issue of climate change is now well known and numerous studies are carried out each year about the influence that human activities have on it. The building and construction sector is estimated to play a relevant role in this, by being responsible for up to 38% of the global CO_2 emissions (Hamilton et al. 2021). Considering the overall energy consumption of buildings, operational energy is usually, by far, the highest contributor, estimated to be around 80 and 90% of the total (Ramesh et al. 2010), and it is strongly determined by the building envelope, which is the part of the building responsible for the interaction between the indoor and the outdoor environment. As a consequence, research about building envelopes led to an increasing interest in the development of new strategies, technologies and materials aimed to improve its efficiency and performance, especially in terms of energy control.
Considering the efficiency of building envelopes, the transparent fraction of a facade is one of its most relevant components, being responsible, on average, for around 30% of the overall energy demand of the building (Hee et al. 2015). The need to fulfil its main feature, visual transparency indeed, affects this component negatively from a thermal perspective, making it responsible for higher thermal losses in cold periods and solar gains in hot periods, in comparison to the opaque fraction of the facade. Transparent components are the only ones capable of supplying a wider range of needs: they provide the indoor space with natural light, allowing solar gains, they provide a view to the outdoors and improve the occupants' well-being (Woo et al. 2021; Ko et al. 2020). Moreover, facade transparency is an element of great relevance in architectural design. All these features make the transparent components essential in facade design, thus making it necessary to focus on how to make it more efficient, rather than reducing it. Despite the technological progress, the transparent components still constitute a weak part of the building envelope. In particular, the effect of glazing on undesired solar gains is probably the most impactful: in most of climates, mainly hot climate regions but also moderate climate ones, the cooling load is the highest component of the energy demand, having to compensate for the solar gains allowed by glazing. In addition, the issue of cooling loads is expected to become more relevant in time due to the increasing temperatures consequently climate change. From this perspective, it is relevant to limit or even prevent overheating of indoor spaces by controlling the solar gains through transparent components in building facades.

1.1.2. Auto-responsive technologies and passive smart windows

One of the most challenging issues to address at the moment is the increasing need for control of solar radiation and heat gains according to the changing weather. As a consequence, researchers and designers started looking for solutions that are not static but dynamic (Juaristi et al. 2018), thus allowing the same system to exhibit different performances depending on the indoor and outdoor conditions. Facade systems capable of adapting their behaviour in time according to the external weather or to the occupancy are called adaptive facades (Loonen et al. 2013). Auto-responsive technologies are

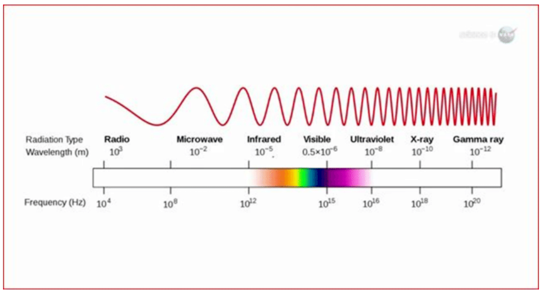
adaptive facade components that operate in an intrinsic mode, responding to the variation of specific external stimuli, such as temperature, radiation or voltage, with a reversible change in their properties (Santos A et al. 2020). Auto-responsive technologies, therefore, operate autonomously and passively, without the need for any external control by either an operator or an automatised system (Juaristi et al. 2018).
Among these, many technologies have been developed and experimented with. Given the relevance of the impact of the transparent fraction on the facade, it was chosen to address the so-called passive smart windows; their glazing units are provided with specific layers that enable the dynamic control of transmittance of the solar radiation, as a direct response to the change in the environmental conditions, without the need of external control (Wang et al. 2021).
The choice of smart windows among other technologies was motivated by the aim to look for a technology that could be widely and easily applied so that it would be appealing to the market. Therefore, the technology needed to be simple and compact: instead of adding new elements to the facade, smart windows include the solar control system within the glazing itself, so that it constitutes a single element, assembled off-site, that can be applied in the same way as usual static windows. This makes them suitable also for renovations, either by replacing the existing glazing or, in some cases, by adding the auto-responsive layer directly on the existing windows (Kim et al. 2022). Smart windows' efficiency depends only on how the material is tuned (so to what quantitative stimulus it would react to) and little on the geographical context, it doesn't require additional space, differently from other passive systems such as double skin facades, and it works autonomously.
Their behaviour is easily predictable since their activation is strictly connected to the weather, but its more delicate component is protected from it, contrary to external shading devices. In addition, it doesn't require any mechanical control system since it relies on auto-responsive reversible property change, thus reducing the need for maintenance and, possibly, the risk of failure.

1.1.3. Aiming for a comprehensive analysis of the impact

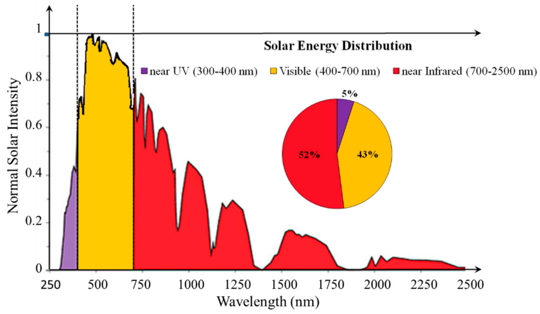
Most of the studies about smart windows do refer to small-scale production, more at the level of laboratory experiments and prototypes, and are not ready for the market yet (Ke et al. 2019), but some manufacturers are already producing several alternatives of auto-responsive glazing and research in early stages is being carried out to improve auto-responsive technologies able to react to the outdoor conditions autonomously. This passive functioning could decrease significantly the need for maintenance and the operational energy for heating and cooling, without requiring any activation energy, that would be needed for similar active technologies instead. So far, the researchers have focused mainly on the improvement of the performances of these systems and materials (Cuce et al. 2015); few real-scale applications are known since rarely the applicability issues, such as ease of production and cost-effectiveness, are addressed. These are very relevant features for the future of these technologies since their appeal to the market is an essential element for their diffusion. However, the research in passive smart windows can be considered relevant as far as those succeed in their original purpose, thus decreasing the overall environmental impact of the buildings. Nevertheless, observations about the environmental impact of these new technologies are rarely found, especially numerical ones. The lack of this information is a relevant knowledge gap since it doesn't allow to assess properly the efficacy of the developments made. Indeed, even though studies can be found estimating the effect of the application of these technologies (Sirvent et al. 2022), these mainly focus on the energy consumption and GWP (Global Warming Potential) of the technology. In contrast, no information was found about other environmental impacts. The lack of information about these factors makes it hard to evaluate the effective impact of the implementation of these new technologies. In case the materials used for the effective functioning of these technologies had an excessive impact, either for their production or their disposal or even worse if those materials induce a worsening in the impact of the End-of-Life of standard windows (e.g. non-detachable coatings, preventing the glazing reuse or recycle), their real contribution to the sustainability of buildings could be more limited than expected.

1.1.4. Passive Smart Windows

The usefulness of Passive Smart Windows lies in their feature of changing their optical properties according to the variation of external stimuli. The optical properties of the materials affect the whole luminous spectrum of the radiation that passes through the window, but not uniformly. Each material modifies differently the percentage of light that is transmitted, reflected, absorbed or scattered, but there are also differences among the frequencies of the electromagnetic waves that compose the radiation. Even though the effect may be similar for all wavelengths (e.g. Liquid Crystals decrease the transmittance and increase the reflectance) (Ke et al. 2019), the variation in values can be significantly different for the various electromagnetic ranges .



(a) Electromagnetic radiation ranges (source: NASA)



(b) Spectrum distribution of natural solar energy (source: (Sentjens et al. 2023))

This aspect is paramount in the development of Passive Smart Windows for energy purposes: indeed, they must always ensure a certain quality of the view towards the outside and provide visible light to the inside but at the same time they must modulate the solar gains. While view and light are related to the visible range of solar radiation (VIS, 380 nm < λ < 720 nm), the heat gains are mostly due to infrared or IR range (Khandelwal et al. 2017), often distinguished in near-infrared (NIR, 720 nm < λ < 2,5 μm) and long wave infrared (LWIR, 2,5 μm < λ < 25μm). Therefore, the differences of optical properties among electromagnetic ranges, specifically visible and IR, are central for their efficacy, since they allow to manage them differently.
Besides this aspect, it must also be considered that the intensity of the solar radiation itself is not uniform among its spectrum, since it resembles the spectrum of a black body; moreover, it changes even more when considering the incident radiation on the window, which intensity for most frequencies is decreased unevenly by the effect of the atmosphere, as shown by figure 1.1b.
For these reasons, the research in terms of the performance of Passive Smart Windows has been focused mainly on the properties of the Auto-Responsive material for the two ranges of visible and NIR radiation, often grouped in a single solar spectrum (sol, 380 nm < λ < 2500 nm) (Costanzo et al. 2016) .

However, different types of PSW follow different physical principles and have their own features. Indeed, PSW can be distinguished into 4 main technologies: Thermochromics, Photochromics, Thermotropics and PCMs. Each technology can be developed by using different materials, which have many variations in mixtures and production methods themselves. This makes the research landscape more articulated and complicated since this affects the availability of the data needed for Life Cycle Impact Assessment.

Table 1.1: Summary of the main Passive Smart Windows typologies

Technology	Stimulus	"On" state
Phase Change Materials (PCM)	Layer temperature	Opaque or translucent
Thermochromic (TC)	Layer temperature	Transparent (dark tint)
Thermotropic (TT)	Layer temperature	Opaque or translucent
Photochromic (PC)	Solar radiation intensity	Transparent (dark tint)

Electrochromic windows are probably the most developed and notorious typology of smart windows, but they are active technologies: they are activated by a voltage difference that must but kept active during the "on" mode of the element (Cannavale 2020). This technology can be integrated with sensors that detect when the activation of the shading mechanism is needed (Favoino, Fiorito, et al. 2016), but this always requires an energy supply from the energy grid and thus cannot be considered a passive

technology.
Following, is a description of the main technologies of Passive smart windows.

Phase Change Materials

Phase Change Materials (PCMs) are materials whose melting point is close to room temperature. The interest in research in these materials has recently increased, especially in the building sector, since the use of their latent heat can be used to store thermal energy. Some also suggested implementing them in glazing systems, exploiting their potential for heat storage and the different visual properties of its solid and liquid phase (Cuce et al. 2015) and some prototypes were developed and applied in some case studies. Nevertheless, the same studies show how PCMs in the solid state are opaque or translucent, thus limiting or eliminating any visual transmittance and making them unsuitable for common use. This doesn't exclude the use of PCMs from applications to the building envelopes, but prevents them from being a suitable replacement for standard transparent facade components on a large scale, especially for buildings of civil use, such as offices or residences; it would indeed prevent vision towards outdoor, having a significant negative impact on the users (Woo et al. 2021). Moreover, their integration in glazing systems is quite difficult: the liquid phase requires the material to be encapsulated (Casini 2016), at either microscopic or macroscopic scale. This implies an increased complexity of the glazing unit, making it more expensive and the components thicker.

Thermochromics

Thermochromic materials react to the variation of temperature with a change in their behaviour towards radiation, thus decreasing the transmittance of the glazing. Generally, the behaviour changes in the material are associated with a transition temperature (T_c): below it the material is more transparent ("off" mode) and above it the transmittance decreases ("on" mode). However, this is a simplification: the materials actually go through a transitional phase determined by a range of temperatures and $T_c$is commonly used to indicate the middle point of this transition, neglecting the amplitude of this range.
Thermochromics are usually applied to windows through coatings or films and can be realised with different materials, which react differently to their transition (Ke et al. 2019): ionic liquids, perovskites and VO2-based nanocrystals, react by increasing their absorbance or by shifting their absorbance bands; hydrogels and liquid crystals instead increase their reflectivity or scattering effect.
The T_c is a very important feature of this technology and depends on the specific material used; part of the research on thermochromics is indeed focusing on tuning the existing materials by experimenting with new mixtures (Du et al. 2022), since the flexibility to produce materials with specific T_c would be very meaningful in improving the operational performance of the technology.
Another interesting aspect of the developments of thermochromics is that their properties vary differently on the radiation spectrum. Thus, Thermochromics can be tuned to decrease significantly their τ_{NIR} while limiting the variation of τ_{vis} (Kamalisarvestani et al. 2013).
This technology can be considered quite developed for several reasons: operational performance and potential for commercialization have already been analysed in different studies (Wang et al. 2021) and few examples of industrial products are already available on the market. Simulations for yearly consumption and benefits have already been carried out (Aburas et al. 2021; Salamati et al. 2019; Haratoka et al. 2023; Arnesano et al. 2021) and LCA calculation can be found (Sirvent et al. 2022), even though covering few impact indicators. Moreover, studies are been carried out to improve the tuning, thus the modulation both of the critic temperature and of the controlled radiation range, and to find cheaper and faster production methods (W. Zhang et al. 2017).

Thermotropics

Their principle is similar to thermochromics, but it works on refraction: when the thermotropic material reaches its T_c, the embedded particles change their refraction index, inducing a scattering effect that rejects a fraction of the impacting light, thus protecting from the solar gains (Kim et al. 2022). For these technologies, different materials have been tested and developed, mainly based on polymers: hydrogels, polymer blends and liquid crystals are among the most studied (Ghosh et al. 2018).
Thermotropic materials can be applied both by encapsulating them in the window cavity, which gives problems in the manufacturing phase thus preventing its industrial applications (Seeboth et al. 2010), or by applying them as a coating. For this last case, removable layers have been developed (Kim et al.

2022), thus making thermotropics suitable for the improvement of existing glazing systems. However, due to their scattering properties, this technology changes the transmittance of the glazing along the whole solar spectrum, including the τ_{vis}, thus making the surface translucent or opaque, depending on the specific material and mixture. The lack of vision through the window limits the possibility of appllication for civil use.

Photochromics

This technology makes use of a photo-induced switching between two states of isomers, changing remarkably its absorption spectrum (J. Zhang et al. 2013). The photochromic material reacts to specific wavelengths, usually in the UV spectrum, which stimulates the compound, based on noble metals, silica and organic compounds (Cannavale 2020). It is reported that some compounds, usually the organic ones, present some issues in the reversibility of the behaviour since the activated state is kept after the end of the stimulus (Ke et al. 2019). The inorganic compounds, instead, are fully reversible and have a fast response time. Nevertheless, the research on photochromic windows has focused mainly on the visual spectrum and rarely on the NIR frequencies. At the current state of the research, little information can be found about the tuning of these materials and no studies were found about the evaluation of their environmental impact, neither with the current laboratory production method nor with the perspective of industrial production. However, the are examples of its commercialisation (Tällberg et al. 2019).

1.2. Problem statement

The research on new smart glazing technologies is evolving at a fast pace, leading to the development of different technologies, each with several variations in terms of properties performance and materials used. These products are being developed to improve the control of solar gains, in order to reduce buildings' energy demand and, consequently, their environmental impact. However, the research has focused mainly on the performance of Passive Smart Windows and less often on other aspects of these building elements, such as the impact of their manufacturing, applicability and disposal. Thus, given a large-scale application of these facade elements, it is currently difficult to assess what their overall impact on the environment would be, considering the balance between the reduction of the operational energy of the building and the embodied impact deriving from these new technologies, especially considering the issues related to their production and disposal.

1.3. Objective and Research questions

1.3.1. Objective

Given the problem statement, the following objective was formulated, as the leading concept of the research work:

"Developing a framework to evaluate the environmental impact of passive smart windows and identify the critical aspects of these technologies from an environmental point of view"

To achieve this objective, the following steps were formulated:

- Identifying, by reviewing existing methods, the suitable energy building simulation model, to provide an optimal set up to test products independently from a specific context, and a proper benchmark, which reflects the current alternative for control of solar gains.
- Setting up a complete framework for the LCA, capable of including and comparing different Environmental Impact Categories (EnICs) in the different phases of the product life cycle
- Producing a method capable of comparing different glazing systems in terms of their environmental impact along their whole life cycle
- Validating and demonstrating the developed method with case studies, to provide an example of its potential by showing the strengths and weaknesses of an analysed passive smart window in comparison with a different solar gain control technology.

1.3.2. Research Questions

Main research question

What assumptions should be considered when evaluating the embodied and operational environmental impact of a Passive Smart Window?

Sub-questions and research methodology

The main question was then articulated in different sub-questions:

1. What assumptions are currently considered for the evaluation of the impact of Passive Smart Windows?
2. To what extent are these assumptions complete and valid?
3. How can the Life Cycle Assessment methodology be appropriately structured to comprehensively evaluate the environmental impact of Passive Smart Windows?
4. To what extent is this framework effective in assessing the impact of a Passive Smart Window?

Those are here analysed, providing the strategy elaborated to answer them:

1. **What assumptions are currently considered for the evaluation of the impact of Passive Smart Windows?**
   As a first step, a literature review will be necessary to gather the currently available knowledge on the application of environmental assessment for Passive Smart Window. To reach satisfying results in terms of comprehensiveness of the analysis, a comparative Life Cycle Assessment (LCA) should be carried out, using a suitable set of impact categories and including all the necessary life stages of the PSW. This implies that the LCA should entail not only the embodied impact, thus related to the production and dismantling of the product but also the operational impact related to its use in a building. Since the latter is strictly related to the application of the window in a building, the Operational phase and the Embodied phase of the PSW's life cycle must be addressed differently. Since the use of the PSW affects the temperature and the amount of daylight in an indoor space, a first literature review will aim to define how to determine the quantity of lighting, heating and cooling energy that the use of the PSW implies in the building. This will be oriented to define a building model that can suitably estimate the energy needs caused by the PSW, in terms of geometry, properties, systems and terms of comparison.
   A second literature review will focus instead on the embodied impact and thus on the application of the LCA method to the PSWs. Usually, the accuracy of the LCA results derives from the precision of the information about the analysed technology but, when a precise building application is not considered, it is necessary to use more generic but still valid assumptions. The literature research will therefore address the approach for those aspects of the LCA that need to be kept as generic as possible, such as the choices in terms of material origin or locations and the consequent parameters, such as transport distances and impact linked to specific regions. It will be important also to understand how to define the boundary conditions of the assessment and what terms of comparison are usually when considering PSWs.
   The literature review will help in the choice of proper software and database for the calculation and in the definition of a suitable functional unit; Finally, it will also provide information on how to choose an assessment method and on the use of results weighting aimed to the calculation of a single index, which may simplify the results interpretation by gathering different impact categories.
2. **To what extent are these assumptions complete and valid?**
   To increase the accuracy of the LCA, it is important to use information and data as precise as possible. A literature review based on research documents may provide data on the most advanced developments in the field of PSWs but it may lack some concerning the actual current practice in the field: when considering a new technology such as PSW, some aspects such as the management of the glass End-of-Life or the estimation of the impact of Auto-Responsive materials may not be fully addressed. Therefore, interviews with experts of the building sectors will be conducted to fill the knowledge gaps left by the literature review.
3. **How can the Life Cycle Assessment methodology be appropriately structured to comprehensively evaluate the environmental impact of Passive Smart Windows?**

The content of the literature reviews and of the interviews will be used to draw a framework aimed to the application of the LCA methodology to the evaluation of PSW's total environmental impact, trying to join the operational and embodied stages of the product. This framework will entail several aspects of the LCA: first of all the definition of the boundaries of the analysis and the sources to be used. Then, the structure of the life cycle of a PSW with the possible variations of it depending on the different conditions to be used, such as the PSW build-up, and the indications of the energy demand simulations. Finally, the approach to use for joining the operational and embodied impact and to interpret the overall obtained results.

4. **To what extent is this framework effective in assessing the impact of a Passive Smart Window?**
   In order to consider the method reliable, its applicability would need to be verified. To this aim, the framework will be tested on a case study: this will see the assessment and comparison of the total environmental impact of a Passive Smart Window (PSW) and a Dynamic Window System (DWS). This application will help in completing what is lacking in the framework. Specifically, it will allow to get a better understanding of some steps of the LCA to be performed, helping on determining what kind of needed data can be found and from what sources; it will also help in structuring a procedure for the interpretation of the results of the LCA and, finally, it will provide general observations on the calculation of the PSW impact.

Thesis Framework and Outline

Each sub-questions was addressed in one chapter of the thesis. The thesis' framework is illustrated in figure 1.2 and an outline of the chapters is following summarised:

Chapter 1 introduces the topic of the research by providing the context and the problem statement, together with the research methodology and framework.

Chapter 2 answers the first research sub-question, providing a theoretical background about LCA and two literature reviews on studies concerning, respectively, life cycle assessments of windows and energy simulation of Passive Smart Windows.

Chapter 3 reports the outcome of the interviews made with experts of the industrial sector with the aim of verifying and completing the information gathered from the literature, as for the second research sub-question.

Chapter 4 defines a framework for the redaction of an LCA of a Passive Smart Window, considering operational and embodied stages. As for the third sub-question, the content of the framework is based on the content of the literature review and interviews.

Chapter 5 applies the framework to a specific Passive Smart Window, in comparison to a Dynamic Window System.

Chapter 6 presents and analyses the results of the case study, describing the environmental impact of the chosen technologies and showing the flaws of the framework, thus allowing its corrections and improvement.

Chapter 7 summarises the findings of the study, highlighting the most relevant factors to monitor for the LCA of Passive Smart Windows and providing suggestions for its improvement and for future related studies

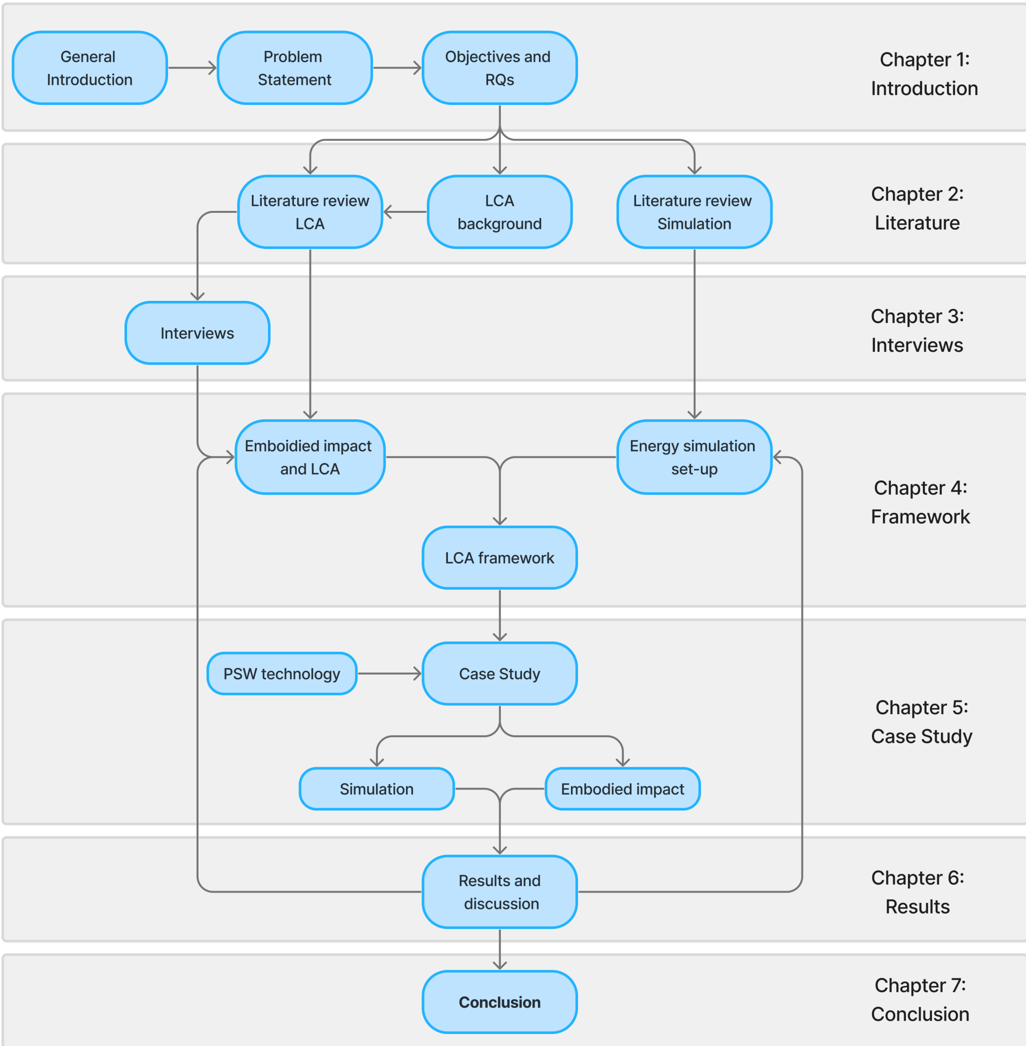


Figure 1.2: Diagram of the research framework used in the thesis, groups different parts

2

Background and Literature Review

2.1. Background on LCA

Life Cycle Assessment (LCA), as defined by the International Organization of Standardization in ISO14040 (2006), is a systematic approach for comprehending and addressing the environmental impacts associated with products throughout their complete life cycle. LCA can be applied for several purposes: identifying of the life cycle to change to improve the environmental impact, informing decision-makers, selecting effective indicators fro the environmental impact and for marketing purposes, such as eco-labelling.
In order to analyse a product, the LCA approach takes into considerations the product system dividing it into interconnected unit processes, each assigned with corresponding flow, thus inputs and outputs. LCA is defined by several principles: first of all, it has a life cycle perspective, thus addressing systematically all stages of the product life with a primary focus on environmental aspects, avoiding those concerning economic and social impacts; it uses a scientific approach, implementing transparency and comprehensiveness. It is an iterative process ,within and between its stages, and has a relative approach based on a functional unit, which serves as reference for all the processes encompassed by the LCA.
Despite all this, the LCA can be realised following different methods and it is therefore subjected to the choices made in this regard. This technique cannot calculate with absolute precision the impact of a product due to several reason: the data are subjected to time and space characterisation, that cannot be reflected completely, the modelling implies some uncertainty and some impacts are relative to the future. Therefore, the results strongly depends on the assumptions made and on the calculations rules that are chosen.

2.1.1. LCA Framework

The LCA procedure is structured in 4 main steps (Fig 2.1):

1. Goal and Scope
2. Inventory Analysis
3. Impact Assessment
4. Interpretation

The goal and the scope express the purpose and the rules for the LCA, defining the boundaries if the system and how to carry out the following steps. The Inventory analysis is the step where inputs and outputs for a product are gathered and quantified throughout its entire life cycle. The Inventory Assessment instead is designed to comprehend and evaluate the the environmental impact of the product

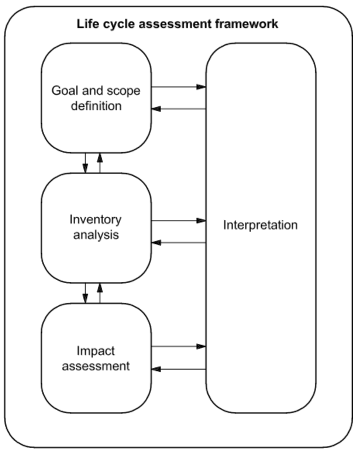


Figure 2.1: Steps for LCA. Source: ISO 14040

system. Finally, the interpretation step evaluates the results of the inventory and the assessment according to goal and scope.
As the scheme suggests, the LAC procedure is not linear but has an iterative nature: each step can show some issues of the previous one and can be used to improved it.

Goal

The goal of the LCA is what leads all the other steps: defining correctly what is the purposes of the assessment is paramount to correctly formulate the framework of the LCA and to take decisions regarding the rules to follow and the assumptions to make. For clearly stating the LCA goal, it is important to specify what application the LCA is intended to have and for what reason it is being carried out for. Together with those, it must be stated the audience the LCA is made for and if the results are meant to be used for comparisons, since the normative ISO 14044 provides some different requirements and restrictions for it.

Scope

Once the goal has been stated, the scope of the LCA must be defined as well; this entails several aspects of the study and defines how the product systems will be shaped, described and calculated (International Organization for Standardization 2006). In case of comparison of different product systems, the scope must be designed with the same way in both cases, so to provide valid terms for the comparison.

First of all, the functional unit (FU) must be defined; this is a quantified performance that the product system must provide and is the reference for all the processes to consider in the LCA. Therefore, the functional unit describes a function and level for performance to be fulfilled by the product, its quantity, its lifespan, its geographical area of competence, e.g. "Complete coverage of 1 m^2 primed outdoor wall for 10 years in Germany in a uniform colour at 99.9% opacity" (Hauschild et al. 2018). The reference flow, thus the amount for product needed to realise the functional unit, is then defined accordingly. In the example mentioned, it is the volume of paint to fulfill the described function. The reference flow is then used to scale all the flows, inputs and outputs, referred to all other processes considered in the Life Cycle. If the LCA entails the comparison of products systems, those should have the same functional unit.

The system boundary is needed to separate the unit processes to include in the analysis from those that do not affect the product system and, thus, do not affect it. It defines which unit processes are considered in the products system and where this must be stopped, verifying that the exclusions made do not affect the results of the LCA. The criteria used to make this choice must be designed following the goal and must be clearly stated and explained, in order to show the logic behind this decision.
The system boundary can be represented by mean of a flow diagram that shows the processes and the relations between them. The ideal systems boundary in crossed only by the elementary flows, so resources used and emissions produced by the system; The system boundary also concerns the level of detail considered for the analysis and the geographical and temporary boundaries of the study. However, the ideal system boundary can rarely be used. For comparisons, for example, it is possible to exclude those unit processes that identical in all the compared systems. Moreover, accounting for all the connected unit processes is practically impossible, given the enormous growth of the number of unit processes to consider when following the value chain. This requires the introduction of cut-off criteria.

The cut off criteria determines what outputs and inputs of each unit process are initially included. The assumptions made to choose it must be clearly stated and the outcome of this choice shall be assessed at the end of the LCA. Several options are possible to choose cut-off criteria, but the most used are mass, energy and environmental impact; this is applied, for example, excluding the flows of a unit processes that represent a fraction of the total inferior to a fixed percentage, often around 0,1%.

The LCIA methodology determines which environmental impact categories are included and what characterization model are used to evaluate the contribution of the elementary flows to these categories. The method must be chosen according or the goal and scope of the LCA, since it has a major impact on the results: the chosen categories determine what aspects are going to be considered in the analysis while the characterisation model defines the factors to convert the LCI analysis results to the category indicator, so what relevance to give to each elementary flow. In time, several LCIA methods have been established and implemented, each with specific features (Hauschild et al. 2018).

Finally, the type of data and the data sources must to be stated. In general most of databases are a mixture of measured, estimated and calculated data. However, the LCI data are provided with several information and the data selected for the LCI should fulfill some data requirements, set accordingly to the goal and scope. This is to ensure that the data used for the study are valid and can represent, with an acceptable level of uncertainty, the processes that are being analysed. The representativeness of the data must be assessed, by ensuring that the time, geographical and technological coverage is respected. The source of the data shall also guarantee their completeness and precision.

Inventory analysis

As aforementioned, Life Cycle Inventory analysis must be executed according to the goal and scope defined for the LCA. This step, entails both the collection and calculation of data regarding the input and output that the scope includes within the system boundary. The data related to unit processes concern their input and outputs, which can be divided in inputs, such as required energy, For the LCI analysis, a sequence of operational steps was defined, that can be described as following:

- Processes identification: before gathering the data, the processes that compose the system value chain must be identified though the system diagram, starting from the reference flow and continuing upstream and downstream.
- Collection: gathering data regarding inputs and outputs of all the unit processes within the system boundary. The data must come with reference to their source, e.g. a database, an EPD or a measurement, and with an explanation of how those were obtained and what unit process they describe. A higher focus and attention should be give to those data that that have a relevant role in the conclusion of the assessment.
- Validation: to confirm that the required quality of the data is achieved, e.g. checking if the mass balance of input and outputs is respected
- Relating data to unit process: the LCI model is built by linking the unit processes and scaling all the flows according to the reference flow. Usually, software do this automatically.
- Aggregating data: the data of the elementary flows of all the unit processes are scaled accordingly to the reference flow and summed, giving the LCI results.
- Refining system boundary: collecting and actually drawing correlation between unit processes can show some flaws in the original system boundary. According to sensitivity analysis results, the boundary can be improved by excluding flows, processes or entire life cycle stages that revealed to be irrelevant or by including new ones that have shown to be significant.

A distinction is made between background processes and foreground processes: foreground processes are those that are the real object of study of the LCA and usually those that can be controlled in some amount by the stakeholders of the analysis. background processes are instead those that belong to the product system but cannot be influenced by the stakeholder of the study.
When drafting the LCI model, multi-functional processes shall be identified; these are processes that produce several co-products, generating an issue with the boundary of the system, since likely only one or few of these co-products belong to the analysed product system. Multi-functionality can be addressed either by subdivision, system expansion or attribution, according to the features of the considered unit process (see 2.1.2).

Impact assessment (LCIA)

In the LCIA lies the largest difference between the relative approach of the LCA and other approaches, such as environmental risk assessment or risk assessment (International Organization for

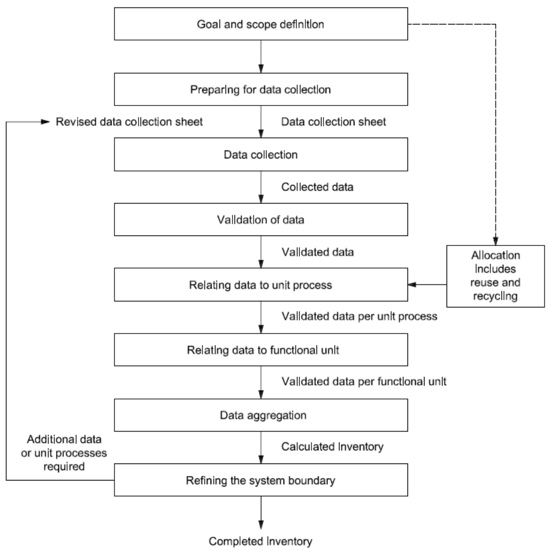


Figure 2.2: Simplified procedure for LCI (source: ISO 14044)

Standardization 2006). It is the step in which the indicators' results of all categories are calculated, giving the LCIA profile of the products system, thus the totals of the impacts for each category and life stage that will be later interpreted. It must be carefully planned according to the goal and scope of the study. Indeed, this step includes some mandatory elements that have a relevant impact on the results of the analysis, such as the selection of the environmental impact categories (EnIC) to consider, of the indicators used to quantify them and of the characterisation models, the classification, thus the assignment of LCI results to the EnIC, and finally the characterisation, so the calculation of the results for each impact indicator representing an EnIC.
Moreover, some additional elements can be added to the LCIA, such as normalisation, grouping, weighting and data analysis. All these aspects can vary significantly and therefore several methods and set of rules have been developed by different experts and institutions; the LCIA elements and the most popular approaches approaches are further investigated in the section 2.1.3.

Interpretation

The interpretation step concerns the assess of the results of the LCIA in relation to the goal and scope to provide conclusions and recommendations about the product system and about the analysis itself. In order to achieve that, the most significant issues of the study must be first identified and the evaluated them according to different approaches (Hauschild et al. 2018). These two steps form an iterative interaction from which temporary conclusion can be drawn. If the conclusions are consistent with goal and scope, they can be integrated in the final report as full conclusion, otherwise the iteration starts again.

2.1.2. Multi-functionality and LCI model approaches

As unit products have multiple inputs, so most of them have several outputs as well and some may have more unit processes as output, which are called co-products. These can be distinguished in reference product and the other products, named by-products. The reference products correspond to the primary function of the process, so the one made available to the users. The by-products cover the secondary functions of the process, so they are relevant to other systems. As a consequence the process, which is defined as multi-functional, is connected to other product systems as well; this collision between different product systems must be solved in order to properly calculate the impact of the considered product system and, to this aim, the normative ISO 14044 provides some hierarchy of solutions.

- *Unit process subdivision*: in this case the process is split in two (or more) parallel processes, each giving one of the co-products. This approach is possible when the production processes are physically separated and the correlated flows can be separated as well, but it is not always applicable

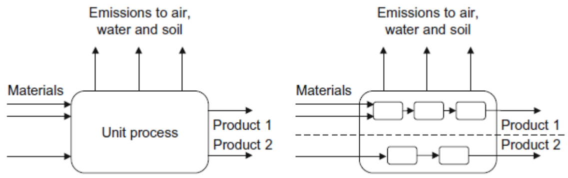


Figure 2.3: Scheme of Unit process subdivision (source: (Hauschild et al. 2018))

- *System expansion (or Crediting)*: a process with multiple products can be credited with the inputs and outputs avoided by the production of its by-products. This is done by identifying an alternative process for the production of the by-product and subtracting its flows from the flows of the investigated unit process. in this sense the original system is expanded to include the alternative process as credited to the

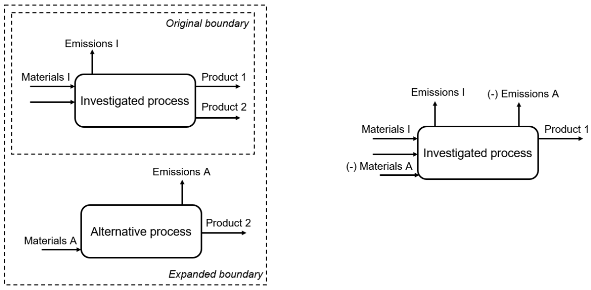


Figure 2.4: Scheme of System expansion (source: Paolo Matricardi)

- *Allocation*: in many cases, it is not feasible to find a functional equivalency between compared systems and system expansion is not possible. In theses cases, the flows of the unit process must be allocated, so divided and assigned, to all the co-products. However, the proportion used to allocate the flow to the co-product may vary depending on the criteria chosen for the allocation; this criteria have an hierarchy as well. The first one is the *causal physical relationship* between co-products: by analysing a process, it can be estimated that some emissions or resources can be clearly allocated to some co-products rather than others. In case this is not possible, the allocation can be based on a *representative physical parameter*, such as mass, when co-products have similar functions. If this option is not possible, *another relationship* must be found; often, the economic value is suggested as parameter

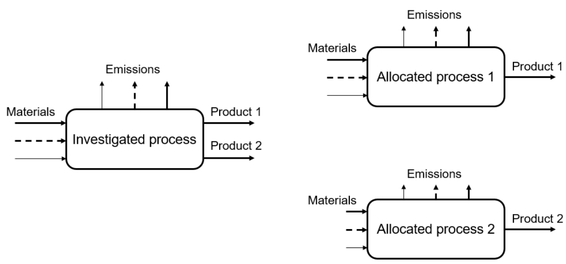


Figure 2.5: Scheme of Allocation (source: Paolo Matricardi)

Following this distinction, two main approaches have been developed foe the modelling of the LCI: an attributional approach and a consequential approach. The attributional approach focuses on the processes that the analysed products has to undergo during its life cycle and analyses ”what impacts the product is responsible for” (Hauschild et al. 2018). The consequential approach, instead, uses a different perspective: it wonders ”what are the environmental consequences of the consuming the product” (Hauschild et al. 2018), thus it focuses on the impacts caused by some decisions and on the consequences that this will have on the market and, consequently, on the consumed products. In this sense, the consequential approach requires a wider knowledge of the economical sector compared to the attributional new. These two approaches can be distinguished by three main aspects: first of all, how multi-functionality is managed: the consequential approach always uses a substitution mechanism, thus the system expansion. Then, the distinction between average suppliers, so all the supplier for a certain product that are present on a market, and marginal suppliers, so those suppliers whose activity gives as reference product an input of the analysed product system; in the consequential approach, only marginal supplier are considered since these are the only ones whose activity is correlated to the demand of the studied product. Finally, following the same principle, the technology level is considered: only the activities which implement sufficiently new, and therefore flexible, production technologies are taken in to account by the consequential model, since those can respond to the variation in the demand. The databases usually provide data for the background system that have already been modelled following on the approaches. Since coherence in the calculation method must be ensured, it is important to choose the approach to be used before starting the data collection, so to be able to gather data that belong to the desired one.

2.1.3. LCIA explanation and methods

Terminology and general explanation

The LCIA consists of several steps; the first three are mandatory, selection, classification and characterisation, and allow to calculate the environmental impact profile of the product system or of a part of it. The other three steps, normalisation, grouping and weighting, are additional and can be used to give a more clear interpretation of the results. Nevertheless, these steps are more subjective, having lower scientific base, and in some conditions are actually not allowed by ISO 14044.

Term	Meaning
Product System	Collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product
Elementary Flow	Substance that enters/leaves the system without previous/subsequent human transformation (resources or emissions)
Environmental Impact	Potential impact on the environment caused by the human intervention on the environment
Environmental Impact Category (EnIC)	Class representing environmental issues of concern to which life cycle inventory analysis results may be assigned (e.g. GWP or Global Warming Potential)
Impact Indicator	Quantifiable representation of an impact category, expressed through an equivalent unit
Equivalent unit	Unit of measurement for a specific indicator (e.g. CO_2^{eq})
Characterisation model	Describes the relationships between the elementary flows of the LCI and the EnICs
Characterisation factors	Factors applied to convert an elementary flow to the selected impact categories. They are derived from a characterisation model
Endpoint indicator	Attribute or aspect of natural environment, human health, or resources, identifying an environmental issue giving cause for concern
Midpoint Indicator	Indicator located along the impact pathway between emissions/resource consumption and the endpoint indicator
Impact Score (IS)	Value assigned to an impact category as result of the characterisation step in the LCIA of a product system
Input	Product, material or energy flow that enters a unit process
Output	Product, material or energy flow that leaves a unit process

Table 2.1: Terminology for LCIA according to Hauschild et al. (2018)

Selection: this step concerns the choice of several aspects of the LCIA and it is carried out in the scope definition, according to goal and scope of the study. First of all, it includes the choice of the environmental impact categories (EnICs) to be considered for the analysis; these must ensure that the LCA results will effectively express the environmental impact of the product system. This means that the categories should, as much a a possible, cover the complete range of impacts that the product could provoke, without being redundant. Indeed, the categories' choice should avoid the issue of double counting of impacts and the risk of burden-shifting between categories. Each category must then be represented by a category indicator and by a respective equivalent unit, to which all the elementary flows will be referred to. This is done by mean of a characterisation model, thus a set or matrix of calculated characterisation factors used to covert each elementary flow to each of the selected categories. In time, several LCIA methods were proposed and established based on the studies of experts. Each is based on specific assumptions and integrates a set of categories, with specific indicators, equivalent units and correspondent characterisation factors; more information about these methods and about their differences are reported in the section LCIA methods (2.1.3).

Classification: in this step, all flows are assigned to the impact categories that they affect. It is to be noticed that each elementary flow can affect multiple categories; this can happen in a parallel mode, so affecting simultaneously several impacts in the environment, or in series, thus producing effects that cause themselves other impacts. This knowledge belongs to experts of the sectors and is expressed by the characterisation factors within the characterisation model methods.

Characterisation: this step concerns the calculation of the impact scores. After the calcification is made, the impact score IS_j is calculated by summing the product of each elementary flow value E_i , multiplied for the respective characterisation factor for that category $CF_{i,j}$:

$$IS_j = \sum_i E_i \times CF_{i,j}$$

As mentioned, the results of the characterisation can already be used for the checks and uncertainty and sensibility analysis, but additional steps can be taken as well. However, it is to be noticed that ISO 14044 doesn't allow the use of normalisation and weighting for comparative LCAs aimed to be disclosed to the public.

Normalisation: this step is often used when there is the desire or need to compare the impact of different categories in the same product system. The calculated scores for each category (IS_j) are compared to those belonging to a reference system (${IS_j}^r$), thus normalising the metrics of the results. Typically, the normalisation reference is divided by the reference population (P^r) The references are typically geographical areas, industrial sectors or a baseline scenarios. Normalisation can be internal, when referred to another scenario formulated in the study itself, or external. To calculate the normalised results, Normalisation Factors (NF) are used; these can be included in the LCIA methods and are calculated as the reciprocal of the IS of the reference system, sometimes divided by the population of the reference region:

$$NF_c = \left(\frac{{IS_j}^r}{P^r}\right)^{-1}$$

Finally, the normalised scores are calculated by multiplying the Impact scores by the respective NF:

$$NS_j = IS_j \times NF_j = \frac{P^r \times \sum_i (E_i \times jF_{i,j})}{IS_j^r}$$

The reference system can be production based, so the reference region affected by the production activities, or consumption based, so referred to the region that the system product affects when consumed. Of course, the reference system used has a major influence on the outcome of this step, so it must be chosen avoiding all possible biases. In addition, normalisation must be seen as a tool to visualise the relative changes in each category, not as a way to compare them directly. A category whose impact decreases (relatively) more significantly than a second, may still be way more impactful on the considered system. So far, no clear guide to normalisation sets has been found. However, it was noticed how normalisation methods have been developed for specific LCIA methods (Rosenbaum et al. 2017; Database & Support team at PRé Sustainability 2022); some of those are implemented directly on database and software.

Weighting: this step converts the various impact scores in one single final score. It allow to prioritise the categories and to aggregate the impact scores, so to make comparisons across different categories. This is done by assigning each category with a weigh and calculating the end score (ES) as a weighed sum of the impact scores:

$$ES = \sum_j NS_j \times w_j$$

However, it is to be noticed that there are no scientific basis for weighting: the choices made are always profoundly influenced by subjective choices, which should reflect the the stakeholders' values. For this reason, results of weighting cannot be be disclosed to public in comparative LCAs. Seldom, normalisation factors sets include weighting sets as well, but these, as aforementioned, are significantly more rare.

Grouping: Categories can also be grouped and additionally sorted or ranked according to their results or to a given hierarchy defined in the goal and scope.

LCIA Methods

A complete and updated overviews of the available LCIA methods are not very common; the most recent studies that were found in literature are the works from Rosenbaum et al. (2017) and Wu et al.

(2020) . these cannot fully cover the complete range of existing LCIA methods, but they still provide a reliable source by listing and explaining.
According to the book of Rosenbaum et al. (2017), all current LCIA methods use some common assumptions for their implementations. First of all, steady-state and linearity, so the impacts related to each elementary flow is assumed to be steady in time and to be directly proportional to the amount of the flows. Conservation of mass and energy is another important principle., together with relativity, thus the expression of impact values in relation to the chosen functional unit. Parsimony and best estimates are also important principles: they point out how the modelling of the impact must be balance between the needed complexity and the highest possible simplicity, while using as much as possible an average values so to avoid biases. Finally, potential impacts are assumed to be used, so not actual values or risks but inventory data integrated in time and space.
Issues such as average and marginal modelling are also taken into account, but those are already accounted for in the system model choice.
Rosenbaum et al. (2017) later identifies 11 most commonly use midpoint impact categories, explaining what problem they represent, how the underlying environmental mechanism can be described and the logic behind the characterisation models. The considered categories are Climate Change, Stratospheric Ozone Depletion, Acidification, Eutrophication, Photochemical Ozone Formaation, Ecotoxicity, Human Topxicity, Particulate Matter Formation, Land Use, Water Use and Abiotic Resource Use. Finally, it makes a comparison of 8 main LCIA methods, namely CML-IA, TRACI 1.0, IMPACT 2002+, EPID 2003, ReCiPe2008, TRACI 2, ILCD and IMPACT World+. However, two aspects need to be pointed out: the book does include the most updated methods, as it is clearly stated about ReCiPe2016, and the last information included refer to the knowledge of mid 2017. Moreover, the comparison of methods is mostly an analysis that considers several technical aspects of how each category is treated, and so how the respective impacts are calculated. Therefore, it doesn't give recommendation on the use of each of these methods but leaves the judgement entirely to the reader, which has to base their choice on their expertise in the field of environmental impact analysis.
According to Wu et al. (2020), the LCIA methods can be classified in resource-based and emission-based and lists the most popular ones. The resources-based approaches analyse the consumption of inputs taken from the environment while the emission-based ones use assessment models to assess the emissions caused by the product system. Those are methods are reported and shortly described in tables 2.2 and 2.3; for the emission-based methods, the corresponding categories are reported as well.

Table 2.2: Most popular resource-based methods (Wu et al. 2020)

Name	Description
Cumulated energy use	All primary energy use along whole life cycle
Ecological footprint	All biologically productive land/sea area needed for the production/absorption of waste

The great variety of existing LCIA methods is a known issues also for the industry; LCA software integrate several of them, but the users often struggle in understanding the differences among them, which prevents them from an conscious choice of the most suitable method for their study. Therefore, LCA software providers developed manuals to support the users in this choice (Database & Support team at PRé Sustainability 2022): here methods are separated in different groups, according to the geographical context (European, Global, North-American) or on the issue the consider (Single issue, Water-footprint). Among those, CML-IA and Ecological Scarcity 2021 are mentioned as European methods, together with EN 15804 +A2 (the updated regulation for EPDs in the EU) and ILCD. For North America, TRACI 2.1 is described, while IMPACT World+ and ReCiPe2016 is are among the global methods.
It is relevant to point out that ILCD (international Life Cycle Database) is actually a wider platform developed by the European commission to provide a more uniform system for the redaction of LCAs in the EU. It includes a database as well as specific tools and digital format for the use of data for LCAs. ILCD was later used as a starting point to develop the Environmental Footprint framework, developed by the Joint Research Center of the European Commission too (FAZIO et al. 2018): EF has however several differences, including modelling and characterisation of some categories, and

provides guidelines and methods for the LCA of products (PEF) and organizations (OEF). Since its first release in 2013, with its pilot phase, EF has been continuously updated and improved with new data, guidance but also characterisation, normalisation and weighting factors.

Table 2.3: A selection of the emission-oriented LCIA methods (Wu et al. 2020)

Method	Description	Midpoints	Endpoints
CML	It considers midpoint impact categories, 21 categories, 9 of which are baseline while the others can be excluded	Fossil, Nuclear, Primary forest, Biomass, Geothermal, Solar, Wind, Water	N/A
Eco-indicator 99	It replaces Eco-indicator 95, and covers all emission categories and parts of the resource categories	Climate change, Ozone layer depletion, Acidification/eutrophication, Carcinogenic, Fossil resources, Ionizing radiation, Ecotoxicity, Land use, Mineral resources, Respiratory organic, Respiratory inorganic	Human health, Ecosystem quality, Resource depletion
IMPACT 2002+	It is mainly based on Eco-indicator 99 and CML 2002 linking 14 midpoint categories to four damage categories	Human toxicity, Respiratory effects, Ionizing radiation, Ozone depletion, Photochemical oxidant, Aquatic ecotoxicity, Terrestrial ecotoxicity, Aquatic acidification, Aquatic eutrophication, Terrestrial acid/nutr, Land occupation, Global warming, Non-renewable energy, Mineral extraction	Human health, Ecosystem quality, Climate change, Natural resources
IMPACT World+	it assesses local and regional impact categories and it is based on IMPACT2020+ and other methods	Human toxicity, Photochemical ozone formation, Ozone layer depletion, Ecotoxicity, Acdification, Eutrophication, Water, Land use, Resource use	Human health, Ecosystem quality, Resources and ecosystem services
ReCiPe 2016	It is a follow up of Eco-indicator 99 and CML 2002 methods that integrates and harmonizes midpoints and endpoint approaches	Climate change, Ozone depletion, Terrestrial acidification, Freshwater eutrophication, Marine eutrophication, Human toxicity, Photochemical oxidant formation, Particulate matter formation, Terrestrial ecotoxicity, Freshwater ecotoxicity, Marine ecotoxicity, Ionising radiation, Agricultural land occupation, Urban land occupation, Natural land transformation, Depletion of fossil fuel resources, Depletion of mineral, Depletion of freshwater resources	Human health, Ecosystem quality, Resources
ILCD 2011 Midpoint	It analyses the emissions into air, water and soil, as well as the resources consumed in terms of their contributions to different impacts on human health, natural environment, and natural resources	Climate change, Ozone depletion, Human toxicity, Particulate matter/respiratory inorganics, Photochemical ozone formation, Ionizing radiation impacts, Acidification, Eutrophication, Ecotoxicity, Land use and resource depletion	N/A
TRACI 2.1	It is a tool for the reduction and assessment of chemical and other environmental impacts. It is a midpoint oriented LCA method	Acidification, Ecotoxicity, Eutrophication, Ozone depletion, Smog depletion, Climate change, Resource depletion (fossil fuels), Human health (air pollutants criteria, carcinogenic, non- carcinogenic)	N/A

2.1.4. Structure for LCA for buildings and building components

Besides all the considerations about the LCA procedure itself, it is also useful to analyse the life cycle of the product itself. The life cycle of an objects is usually divided in three main stages: *Pre-use* (A), Use (B) and *Post-use* (C); A fourth stage can be added, to consider the the benefits that can be introduced by considering alternative ends of life alternatives and implementing actions for circularity beyond the life cycle (D).
Concerning the construction sector, the normative EN15804 (CEN (European Committee for Standardisation) 2019) provides the rules to conduct EPDs of building elements, thus giving a framework for their LCA as well; the normative identifies stages of the life cycle and divides them in modules, so to improve the clarity in the distinction of the processes involved in the element's life cycle.

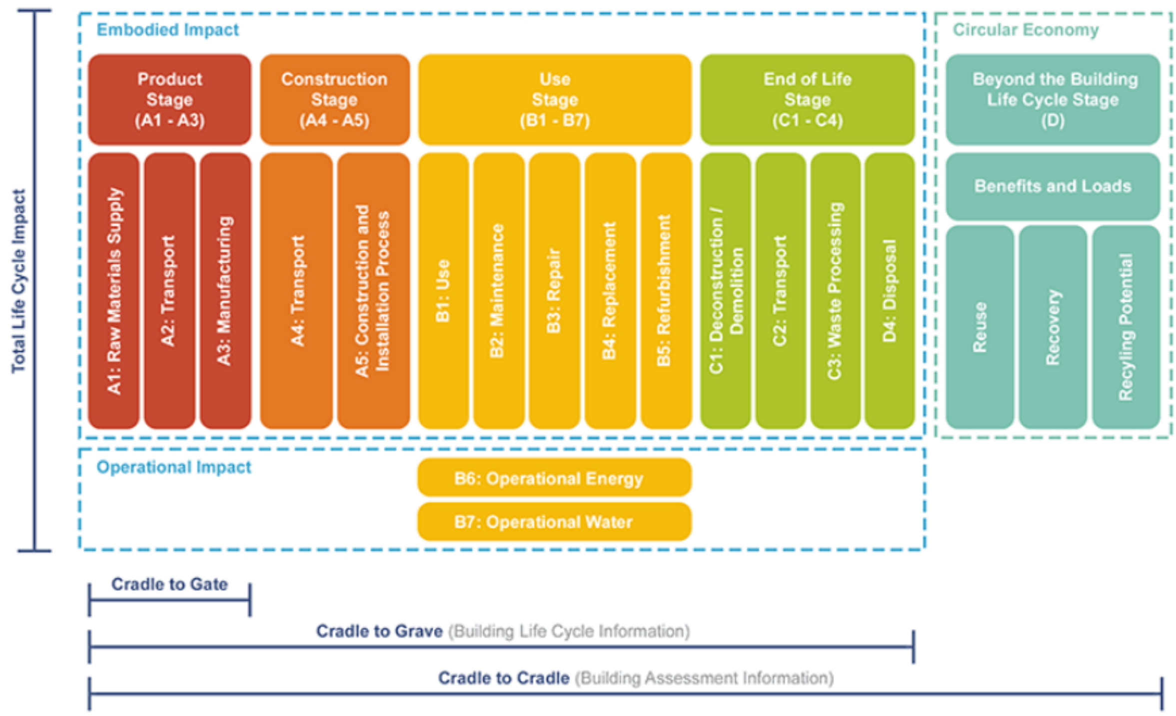


Figure 2.6: LCA modules in building elements according to EN15804 (source: BNP media)

The Pre-use stage is split in two: the Product stage and the Construction stage. The first one refers to all the processes that a product needs to undergo being transported on site, while the construction stage concerns with the on site activities. The Use stage, concerns the operational impact of the element, so the consumption of energy and water in the building due to the use of that element, and the embodied impact, so the impact for the activities that guarantee the operation of the product during this stage. Then the Post-use stage or End-of-Life (EoL) is accounted for. The benefits coming from circular choices all along the life cycle should be accounted for in the Benefits stage. More in detail, the modules, also shown in Fig2.6, are divided as following:

- Product stage:
  - A1 - Material Supply: procurement of the raw materials, both from virgin sources or from recycled materials.
  - A2 - Transport: movement of the raw materials to the manufacturing site
  - A3 - Manufacturing: all the processes that the materials have to undergo in order to become the products used in the building
- Construction stage:

  - A4 - Transport : movement of the products from the manufacturing site(s) to the building site
  - A5 - Construction or installation: all the operations necessary to make the product operative in the building

- Use stage:
  - B1 - Use: emissions or consumption related to the actual use of the product
  - B2 - Maintenance: technical and administrative actions needed to guarantee the correct operation of the product on site
  - B3 - Repair: all the actions aimed to substitute only some components of products, including the procurement of the new components and the disposal of the replaced ones.
  - B4 - Replacement: all the actions aimed to substitute the product, including the procurement of the new element and the disposal of the replaced one.
  - B5 - Refurbishment: actions carried out as concerted programme for the replacement of elements in a whole part of the building
  - B6 - Operational energy use: energy use during the operation of the product
  - B7 - Operational water use: water use during the operation of the product
- End-of-Life stage:
  - C1 - Deconstruction: all operation concerning the removal of the element on site, at the end of its service life
  - C2 - Transport: movement of the products and wastes to treatment and disposal sites
  - C3 - Waste Processing: all actions on the waste material, including their separation and treatment of materials meant for reuse/recycling or energy recovery
  - C4 - Disposal: pre-treatment and management at disposal site and relative impact. Also, all the emissions or resource consumption related to second life treatment
- Benefits stage: this accounts only the net benefits given by the implementation of circular use of wastes. These benefits must be coherent with the flows that exit the product system. The avoided impacts given by the allocation of by-products do not belong to this module but to the module of their unit process.

It is not always necessary to involve all the modules in the LCA but some can be skipped depending on several conditions. This is related, firstly, on the focus of study: depending on its goal, the LCA may exclude by definition some parts of the product's life cycle; besides cradle-to-cradle analysis, which involves all the aforementioned modules, the study can have a cradle-to-gate perspective, so considering for example just the production of the product (A1 to A3) or a cradle-to-grave perspective, thus including all life stages of the product but not considering the possible circular benefits (A1 to C4).
Modules can also be excluded when they do not belong to the life cycle of the specific product. This can be the case for example for the refurbishment in LCA of foundation or the operational water of a lighting system.
Moreover, in case of comparative studies, the processes that are identical in all the considered products can be disregarded, since they do not provide any additional information to the comparison. However, this exclusion must be conducted carefully since it can affect the final results: the exclusion of the most impactful process can enhance the differences between options but, at the same time, can make some results appear more meaningful than they would be if compared to the whole life cycle. More importantly, if two compared systems differ in terms of repair, refurbishment or replacement, some activities may need to be accounted for in different amount and thus cannot be simply be excluded even if identical.

2.2. Literature Review: LCA

2.2.1. LCA of PSW and windows

The research was carried out on Scopus and started as quite narrow, focusing on comparative studies of passive smart windows: *(window OR glazing OR glass) AND (lca OR (life AND cycle AND*

assessment)) AND (comparative OR comparison OR compare) AND (thermochromic OR responsive OR smart OR photochromic), from 2011 to 2023. This research gave only one relevant result (Sirvent et al. 2022), which was already known. Sirvent et al. makes indeed a comparative LCA of a thermochromic technology and a static glazing.
More research attempts were made to extend the sources to windows comparative studies and to windows in general: *(window OR glazing) AND (LCA OR (life AND cycle AND assessment)) AND (comparative OR comparison OR compare)*, still from 2011, and *(window OR glazing) AND (LCA OR (life AND cycle AND assessment)) AND (facade OR envelope OR skin)*, from 2017, so to include the possible use of the LCIA method ReCiPe2016. Again, the results were filtered and several related studies were found.
The analysis of the background for LCA (section 2.1) highlighted some aspects to be analysed in the selected papers, such as software, database, LCIA method and system model, while others, such as window-to-wall ratio and considered End-of-Life scenarios, depended on the focus of the study on impact and energy contribution within the building. The main findings are reported in table 2.4 and following explained.

LCA software, database and system models

The choice of the software has limited relevance on the results of the study as long as reliable software is used; usually the choice depends on the tools available to the practitioner (Hauschild et al. 2018).
SimaPro and GaBi are among the most popular software, but a license is needed for their use. OpenLCA is considered equally valuable, it has indeed been used already for academic research (Sirvent et al. 2022; Megange et al. 2019; Elkhayat et al. 2020) and its access is free, without limitations in its functions. Tally (Phillips et al. 2020) is instead a plug-in for Revit, BIM-oriented design software: it is, therefore, more appropriate for projects than for product research and to evaluate several design choices in a faster, but rougher, manner. Finally, Athena IE (Azari 2014) is a ”whole building tool” designed for North America and connected to its own database.
The most used database, both in the construction sector and for windows is EcoInvent, as proved by most of the analysed studies (Sirvent et al. 2022; Megange et al. 2019; Elkhayat et al. 2020; Pomponi et al. 2016; Feehan et al. 2021; Phillips et al. 2020; Owsianiak et al. 2018). Some studies use databases provided by the software adopted for their calculation, but those are based on EcoInvent itself, as for Athena IE(Azari 2014) and GaBi (Tushar et al. 2022). In some cases, when specific relevant processes are missing in the database, those can be estimated from primary sources, thus literature or official documentation, such as EPDs (Sirvent et al. 2022; Elkhayat et al. 2020): This procedure is clearly indicated, reporting the source, the method and calculation used to obtain the impacts for those specific processes. Since different databases can be modelled with different criteria, it is important not to mix data from different sources, unless the compatibility has been verified (Hauschild et al. 2018) .
Several studies do not specify clearly what system model they used (Tushar et al. 2022; Azari 2014; Feehan et al. 2021; Phillips et al. 2020) but all the other studies (Sirvent et al. 2022; Megange et al. 2019; Elkhayat et al. 2020; Pomponi et al. 2016; Owsianiak et al. 2018) explicitly used an attributional system model. According to Pomponi et al., this system is the most suitable due to the focus on the facade systems as a product. Among all the reported studies, Citherlet et al. (2000) (2000) doesn't mention any specific database, LCA software or system method. This could be probably attributed to the early publication of this study: the main normative wasf published 6 years later than Citherlet et al., so it could be legit to assume that a framework for LCAs was not clearly established yet, or at least that the authors did not consider necessary to report the relative information in their paper; this could explain the lack of information in this study.

Table 2.4: Literature review for the LCA of PSW and glazing

Source	Window type	Software	LCI Database	System model	LCIA method	Location	Functional Unit	Lifespan (years)	Normalisation	Weighting
Sirvent et al. (2022)	Thermochromic	openLCA	Ecoinvent 3 + literature	cut-off	CED + IPCC2013	Spain	”maintaining the office room at a comfort temperature (21–24°C) for 20 years, while the window area to fulfill this functional unit was the reference flow.”	20 (glazing); 10 (layer)	no	no
Tushar et al. (2022)	static	GaBi	GaBi2018	n/a	TRACI2.1	Australia	1 m^2 of window	60 (building)	no	no
Megange et al. (2019)	static	openLCA	Ecoinvent 3	cut-off	dynamic-LCA on CO2 and CH4	France	”to close a permanent opening of 1 m^2 in an outer wall, while allowing the passage of light, manual opening / closing, thermal insulation, water-tightness, resistance to wind, air permeability, and acoustic insulation, in accordance with the rules of art and RT2012.”	*(only product stage)*	no	no
Azari (2014)	static	AthenaIE	(mixed)	n/a	TRACI	USA	”Building envelope to enclose a hypothetical two-story office building in Seattle, US, with 3600-square-foot floor area and the service life of 60 years”	60 (building)	no	no
Elkhayat et al. (2020)	static	openLCA	Ecoinvent 3 + EPDs + literature	cut-off	impact2002+, 6 EnICs	Egypt	”3428m^2 façade area, which encloses a seven-story office building in New Cairo, Egypt, as a hot desert climate zone.”	60 (building); 30 (window)	benchmark (int)	no
Pomponi et al. (2016)	static	SimaPro	Econinvent	attributional	ReCiPe2008H	UK	”1 m^2 of the façade with a life span of 50 years.”	50 (building)	no	no
Feehan et al. (2021)	static	n/a	Ecoinvent3	n/a	ILCD 2.0 Mid, 3 EnIC	Ireland	1m^2 floor	50 (building); 25 (window)	no	no
Phillips et al. (2020)	static	Tally (Revit)	Ecoinvent + GaBi data	n/a	TRACI, 5 EnIC	USA	building	60 (building); 40 (window)	no	no
Citherlet et al. (2000)	static	n/a	n/a	n/a	GWP, AP, Pocp, energy (non ren)	Switzerland	m^2 of glazing	30 (glazing); 45 (window)	no	no
Owsianiak et al. (2018)	static	GaBi 4.3	Ecoinvent 2	attributional	ReCiPe2008H	Denmark	m^2 of glazing	20 (glazing)	EU27 (+ uncert 95% interv)	no

LCIA methods

Before analysing what methods were the most used when conducting LCA of windows, a general overview of up-to-date existing methods was needed to understand which are now available. It important to remember, indeed, that LCIA methods are often upgraded, by updating their characterisation factors or by modifying the categories and the calculation methods behind them. Therefore, a short summary of these methods is given, based on a LCA software manual (Database & Support team at PRé Sustainability 2022) and a review on LCA (Rosenbaum et al. 2017).
CML-IA is an European method that proposes a set of 10 obligatory environmental categories, defined baseline and suitable for simplified studies, and provides additional ones for a more complete assessments. Ecological Scarcity 2021 is an update of previous methods and considers up to 20 EnICs, associating them with specific weighting factors. However, these method is rarely mentioned in the reviewed literature and it has not been found to be used for windows or facades.
IMPACT World+ has a global scope and entails both midpoint and endpoint categories, considering also regional impacts and long-term effects. ReCiPe2016 includes 18 midpoints EnICs, which can be aggregated in 3 endpoints EnICs, but it also uses different perspectives to assess their effect, namely I or individualist (short-term based, optimistic expectations towards technology development), E or egalitarian (long-term based, precautionary approach) and H or hierarchist (intermediate, most popular).
TRACI 2.1 is a program developed specifically for the US context, providing both average values for the country and values for more specific locations. The latest version provides 10 midpoint categories.
Single issue methods were also listed, but these are not considered, mainly due to the issue of burden-shifting (Hauschild et al. 2018): the analysis of single EnIC rather than set of EnICs give a partial view of the issue and prevents from monitoring the several different impacts that products have on the environment; the existence of several EnICs and the respective different characterisation methods derives indeed from the disproportional impact the product can have on different aspects of the environment. Therefore, the use of single issue methods, as well as the exclusion of some categories from an established set, can be misleading and hide impacts that could potentially result in high environmental damages (Hauschild et al. 2018).

From the selected literature, it resulted that not all studies refer to the most popular or well known LCIA methods, and, more surprisingly, they often provide quick or superficial explanation for their choice. This is actually explained by Hauschild et al., who point out how often LCA practitioner do not apply a systematic decision-making process for this choice but they rely mostly on the familiarity with the methods they already used or on the advice of colleagues. However, a geographical correlation can be noticed: TRACI is used by studies made in the USA (Azari 2014; Phillips et al. 2020), which is quite coherent since the scope of the method, and in Australia (Tushar et al. 2022); all of these study however consider only a reduced number of EnICs, between 3 and 6. It was not specified if that was due to limitations in data or to the authors' choice. Feehan et al. (Ireland) makes use ILCD midpoints available on Ecoinvent database, namely Climate change, Fossils, Minerals and metals, but do not provide explanation on the choice of this categories. Elkhayat et al. (Egypt) chooses 6 EnICs from IMPACT 2002+; the method is reported to be the same used in previous studies, but there is no explanation of the categories selection. Sirvent et al. (Spain) uses two single issue methods, Cumulative Energy Demand method and IPCC2013 (Global warming potential), thus focusing deliberately on one aspect; however, this is the only paper studying a PSW and it is possible that the lack of data on the production and end-of-life of the Auto-Responsive layer suggested to focus only on the impacts that are the most frequently analysed. Pomponi et al. (UK) and Owsianiak et al. (Denmark), instead, use ReCiPe2008H, which is based on European context, and enhance the importance of considering several indicators, underlying how single issue studies neglect relevant impacts, also for facades.
Citherlet et al. do not mention make any reference to specific method used, but they specify the categories used, Global warming Potential, Acidification Potential, Photosmog and Non-renewable Energy) without specifying the characterisation model used. As already assumed for system method and database, probably Citherlet et al. didn't consider any established method because of their development at the time. Finally, the work of Megange et al. focuses on a dynamic LCA, thus modifying how the impact is calculated depending on time; however, this study focusing only on emissions related to Global Warming, namely CO_2 and CH_4.
In general, the analysed literature doesn't provide solid criteria or suggestion for the choice of a LCIA method, besides confirming the need to consider a wide range of categories. However, Wu et al. re-

ports how the European Commission recommends to use the RACER approach for the selection of the EnICs; the name o the approach is actually an acronym of characteristics that the indicators should fulfill in order to be selected: Relevant, so "linked to the target" of the study; Accepted, by the stakeholders of the study; Credible, meaning unambiguous and provided with transparent calculation; Easy to monitor; Robust, concerning the characterisation model used.

Normalisation and Weighting

Few studies (Elkhayat et al. 2020; Owsianiak et al. 2018) carry out a normalisation at the end of the LCIA: Elkhayat et al. makes an internal normalisation, taking its benchmark product as reference and comparing all the new products tested to it; Owsianiak et al. instead used the established normalisation set for the European Union EU27 for ReCiPe2008H.
None of the studies applied any weighting to their final results. This is probably due to the subjectivity inherent with the weighting process: as specified by ISO14044 (International Organization for Standardization 2006), weighting has no scientific basis and must be carried out carefully and according to the stakeholders interest, since it must reflect the values of all the involved parts. The lack of weighting in research papers could be ascribe to the nature of these documents through the following factors:

- weighting is not objective, so its can be misleading if wrongly interpreted. However, this is true for a countless number of studies in any field and doesn't give a sufficient explanation to the issue.
- these papers are oriented towards a wider understanding of the impact of the processes rather than to decision-making. Weighting give the advantage to have a single parameter to compare between several products or scenarios, thus making strong assumptions on the relative relevance of the impacts but reducing the effort and assumptions to be made during the results interpretation. Nevertheless, some studies are also aimed to provide tools for decision makers (Elkhayat et al. 2020)
- weighting depends to the stakeholders involved in the LCA; a public study doesn't have a specific stakeholder so the choice of a weighting method among other could result inconsistent.

Despite the lack of use of normalisation sets in the scientific literature, several actually exist (Rosenbaum et al. 2017; Database & Support team at PRé Sustainability 2022); these sets are related to the specific geographical areas and are based LCIA methods and are often implemented directly on database and software. The normalisation sets, in their latest versions are reported in 2.5; some are provided with weighting sets as well.

Table 2.5: Normalisation and Weighting sets examples; (*) indicates those available on Ecoinvent (from OpenLCA).

LCIA Method	Normalisation Sets	Weighting Sets
CML-IA(*)	World 2000(*); West Europe 1995(*); the Netherlands 1997(*); EU25(*); EU25 +3 2000(*)	
IMPACT 2002+(*)	Western Europe(*)	Western Europe(*)
IMPACT World+	World 2010	STEPWISE 2006
ReCiPe 2008 (*)	Europe 2000, World 2000	Environmental Prices Dutch (*), Environmental Prices EU28(*)
ReCiPe 2016 (*)	World 2010(*): Midpoint (H), Midpoint (I), Midpoint (E), Endpoint (H), Endpoint (I), Endpoint (E)	*two sets (H and A) for all Endpoint(*)*
ILCD 2011 Midpoint(*)	EC-JRC Global(*); PROSUITE Global(*); EU27 2010(*)	EC-JRC Global(*); PROSUITE Global(*); EU27 2010(*)
TRACI 2.1 (*)	Canada 2005(*) ; US 2008(*) ; US-Canadian 2008(*)	N/A

In the case for ILCD, each normalisation set is paired with a weighting set, and for ReCiPe 2016, where each midpoint set has one or two weighting sets.
It was also notice that the LCIA method Environmental Prices doesn't provide any normalisation set

but two weighting sets: one for the Netherlands and one for EU28. Environmental Prices doesn't propose its own categories and characterisation model but relies on ReCiPe2008H. New editions of Environmental Prices Handbook were published in 2017 and 2023, but it was not understood if the base for those was still the superseded ReCiPe2008 or if an update was made for adapting it to ReCiPe2016. The wider geographical validity of ReCiPe2016 should not be an obstacle to the application of the weighting methods, but the updated values and flows considered may play an important role, without any clear statement by the author of Environmental Prices, its application remains bond to the method ReCiPe2008H.

Functional Unit and lifespan

Products are developed and used to provide a certain function in a system. Therefore, when making an LCA, it is necessary to defines the function that the assessed product is supposed to fulfill; this is even more relevant when making a comparative study. The functional unit must clarify the function to be provided by the product and its performance. this the performance that the analysed product must guarantee and it differs from the reference flow, which is the quantity of product to be considered as reference for all the processes and materials involved in the LCI.
Most of the papers considered the window or a unitised area of it as functional unit; some of those defined it superficially, indicating just the area of the window assessed (1 m^2 of window (Tushar et al. 2022) or glazing (Citherlet et al. 2000)) or the area and the considered lifespan considered (Pomponi et al. 2016), while others gave a more detailed description, mentioning the properties of the windows or of the facade and the performances it had to fulfill: for Sirvent et al. "the functional unit was set as maintaining the office room at a comfort temperature (21-24°C) for 20 years, while the window area to fulfill this functional unit was the reference flow", for Megange et al. it has to "close a permanent opening of 1 m^2 in an outer wall, while allowing the passage of light, manual opening/closing, thermal insulation, water-tightness, resistance to wind, air permeability, and acoustic insulation, in accordance with the rules of art and RT2012", while for Owsianiak et al. it must "Allow daylight into a residential building through a physical barrier, equivalent to light being transmitted through an area of 1.82 m2 with visible light transmittance of at least 0.6, for 20 years". These definitions can be considered more appropriate since they include the performances of the product. Other papers instead considered the whole building envelope or the whole building as a functional unit, but again the definition is quite superficial: Feehan et al. uses "1 m^2 of net floor area, for lifespan of the building of 50 years and one replacement after 25 years", Phillips et al. defines its as "the entire building over an assumed 60-year life" and Elkhayat et al. uses "3428 m2 façade area, which encloses a seven-story office building in New Cairo, Egypt, as a hot desert climate zone".

Operational Energy calculation

One of the issues to address in windows LCA is the integration of the operational energy in the LCA. The operational energy indeed depends on the window performance but also on several factors that are not related to the window itself: for windows, the use of operational energy depends on the energy demand of the building it is used in, thus rising two main distinct problems. On one hand, the building's energy demand, including heating, cooling and lighting, depends on the building itself, so on several aspects concerning the context, the properties of the envelope and the systems of the building; this aspects will be addressed in the section dedicated to the energy simulation (2.3). On the other hand, it is relevant to determine what fraction of the building's energy demand is to be attributed to the window itself. Indeed, the transparent section for the facade is not the only responsible of heat transmittance to the outside: the opaque section of the facade is responsible for lower but still significant heat exchange with the outdoor climate, and the same happens with other elements of the building's envelope, such as the roof. It is therefore important to understand if the whole calculated energy demand must considered operational energy
Despite these considerations, the analysed studies have different, sometimes incomplete, approaches to this matter. Some studies (Azari 2014; Feehan et al. 2021; Phillips et al. 2020) consider the whole building or the whole envelope as functional unit and simulate the energy demand for the whole building, thus reducing the issue of the contribution; however, their choice still doesn't take into account the different impact that the U_{wall} has on this simulation. Elkhayat et al. and Phillips et al. make the building's energy demand coincide with the operational energy, while (Azari 2014) seems not to integrate

it properly in the LCA but to use the energy demand as an additional category in the impact profile of the windows. This last choice is quite debatable, since it is doesn't actually integrate the operational energy in the life cycle but it just adds it on the side, not allowing a proper estimation of its impact on the different categories.
Owsianiak et al. uses a simplified method, avoiding the energy simulation and calculating exclusively the energy losses through the U_{window} and doesn't seem to consider the solar gains through the window; it also avid any considerations on the room size and properties and it neglects the annual variations of the outdoor temperature, disregarding the cooling needs and addressing the heating demand only, giving a superficial and likely misleading estimation of the energy demand of the building. The focus of the assumptions is mainly on the data on the energy mix used to provide the heating: its composition is explained, pointing out how the data are referred to specific regions (namely Switzerland and EU27) and what source was used.
The study from Sirvent et al. integrates the energy demand using the values of energy simulations carried out by Aburas et al., a study on the performance of thermochromic windows; this study considered a cubic office with a transmitting facade, while the other surfaces, were considered adiabatic. The source estimated the energy demand per m^2 of floor surface and Sirvent et al. attributes to the window the energy demand of the whole room, so of the whole facade, not taking into account the contribution of the opaque wall.
Pomponi et al. instead calculates the contribution of the window through the subtraction of the demand with the studied technology (a double skin facade) and with the benchmark technology (a corresponding single skin facade). This approach looks quite reliable but it can be applied in this case since the double skin facade is considered as an additional structure built in front of the benchmark. Moreover, this approach showed some weaknesses: it is highly dependent on the benchmark, it can attribute a negative value to the operational energy (even though no energy is produced but simply saved in comparison to the alternative) and it attributes a null value to the benchmark.
Citherlet et al. also considers a cubic office space with the facade as only transmitting surface, but it also uses a baseline contribution approach: the operational energy attributed to the window is calculated as the difference between the energy demand simulated with the window and the baseline energy demand. This is calculated by simulating the energy demand of the same model where the window is replaced by an element with no energy transmission ($U = 0$ W/m^{2}K). The baseline calculation is supposed to estimate the energy demand due to the opaque wall, that can therefore vary in relation to the U_{wall} and to the WWR, which were not considered by the other method.
Not all the studies integrate the operational energy clearly in their LCA: Megange et al. only considers a cradle-to-gate perspective, considering only the production stage and thus excluding all the other stages. Tushar et al. simulated several different windows with different opaque walls, climates, WWR and frames, in order to derive linear equations based on U value, g value and WWR and determine how these variable affect the energy demands; however, the results of the operational simulation are never integrated or compared directly to the "embodied impact" of the windows, thus the impact of the other stages of the life cycle.

Auto-responsive layer

LCAs related specifically to Passive Smart Window and to Auto-Responsive layers in general are very rare. This was the case both for scientific literature, where the study by (Sirvent et al. 2022) was found, and for the market, where it was possible to find some products but never to access the related impact evaluations. It is still not clear if this is due to the lack of development of EPDs for these products or if the confidentiality of their production processes discourages the companies from publish this data. As a matter of fact, by now the practise suggests to calculate the impact of the production of the AR material and of its application to window by estimation of the impact of all the involved materials and processes, as done by Sirvent et al.

Window to wall ratio

The window to wall ratio (WWR) is a parameter that expresses the portion of facade occupied by the window (or windows); it has a major influence on the solar gains and thermal losses, so it is very important to be considered when analysing the role of windows in the energy demand of buildings or rooms (Phillips et al. 2020). Indeed, several analysed studies (Tushar et al. 2022; Megange et al. 2019;

Azari 2014; Feehan et al. 2021; Phillips et al. 2020) compare the LCA results with different WWR in order to determine correlations between this parameter and the environmental impact of the facade, often aiming to optimise this impact.

Phillips et al. specifically focus on the optimisation of WWR through LCA. However, the most relevant observations to this study lie in the explanation of the three tested values (20%, 40% and 60%): when modelling the envelope in the simulation software, the windows at 60% resulted too tall for the facade, thus implying the lowering of the sill under the window. This shows how 60% could be considered an excessive value. The study also proved the higher WWR to give the worst results not only in environmental impact but also in terms of costs and user satisfaction.
Tushar et al. studies the variation of peak energy demand on WWR (with values between 40% and 60 %, combined with SGHC and τ_{vis}; it confirms that the decrease of the WWR improves the energy efficiency of the building, but it doesn't provide a specific explanation for the chosen values.
Feehan et al. use a default value of 30%, representing the average in Irish offices, but run simulations in several scenarios, combining different values between 10% and 65%. The study concludes that a WWR of 20% is optimal to minimise the energy demand of the building during its use, while higher WWR values correspond to a lower impact in the EnICs considered; this is probably due to the fact that they reduce the amount of opaque facade, typically heavier, therefore diminishing the mass of the envelope. Azari instead considers the full envelope and the effect of the WWR on the overall impact, using the values 40%, 60% and 80%. However, it also points out how the two higher values are not realistic, since the are to high for the US energy code requirements.
When carrying out the LCA of windows, the WWR varies significantly depending on the purpose of the study. Some studies focus on the improvement of the operational energy of the building, which requires lower values of WWR, while others aim to minimise the environmental impact of the envelope, which can benefit from a higher WWR.
However, some studies make use of a single WWR value and keep that constant for all their scenarios, but very different values were considered: starting from these observations mad in other studies, Pomponi et al. suggests a WWR of 25% and Sirvent et al. 69%, while Citherlet et al. and Elkhayat et al. use respectively 25% and 80%, but without giving specific motivations.
Owsianiak et al. doesn't have a value for the WWR since it doesn't consider the window to be included in a facade, thus using a profoundly different approach to the energy demand issue. Finally, one study (Megange et al. 2019) doesn't provide any data or observation on the WWR, since it only consider the production stage of the window and make considerations on the use stage at all.

Parameters: choices on scenarios, comparisons and benchmarks

When making scenarios to be analysed in an LCA, it is important to consider the aim of the analysis carried out: some studies (Tushar et al. 2022; Azari 2014; Pomponi et al. 2016; Feehan et al. 2021; Phillips et al. 2020) aimed to find optimal design parameters for the implementations of windows in buildings, thus focusing on aspects of the window itself and of the facade, such as WWR, orientation, frame materials, wall properties and glazing properties. For these, several calculations were made, compared and ranked, often combining all the possible variable and reaching large sets of results (Pomponi et al. 2016); this is especially the case of Tushar et al., who developed a regression model to find impact correlations among the results of the "thousands of results" found. However, the purpose of these is to define a criteria to choose one of the design options. The works of Megange et al. and Elkhayat et al. focus mainly on the comparison of different glazing alternative, so evaluating less alternatives but still aiming for a design optimisation. However, Elkhayat et al. uses a scenario with different g values for its baseline technology and with an alternative disposal treatment for the Photovoltaic for one of the products analysed (recycling instead of landfill)
Other studies focused, instead, on the differences in the life cycle: Sirvent et al. compares a static DGU and a thermochromic PSW composed of DGU with and adhesive AR film, considering a laboratory scale production and an industrial scale production as two alternative scenarios, so estimating how the impact of the PSW would decrease following the development of an established industry for the product. (Owsianiak et al. 2018) considers different window frames, but also compares a DGU in Denmark with two scenarios: a DGU in EU27 and a TGU in Denmark; the geographical distinction is used to enhance the difference impacts of operational and disposal modules, determined by the changes in energy source and waste treatment method used in the different countries.

Basically all the studies make comparative LCAs some focus on one specific aspect while other combine different parameters. However, the choice of the scenarios is strictly related to the purpose of the research: papers focusing on the minimisation of impacts, often consider a wider amount of parameters and include climate and WWR, thus trying

Considering the benchmark, the only study that concerns a PSW (Sirvent et al. 2022) uses a static DGU as term of comparison. However, the auto-responsive layer evaluated is an adhesive film for refurbishment; for this reason, the life cycles of the compared products (static DGU and TC window) is considered to differ exclusively because of the TC layer and are therefore extremely simplified, so much that the only LCI item for the DGU is the operational energy. All the other studies, compare different variations of static windows. in one case (Citherlet et al. 2000), windows with dynamic shading are considered as well

End-of-Life - EoL

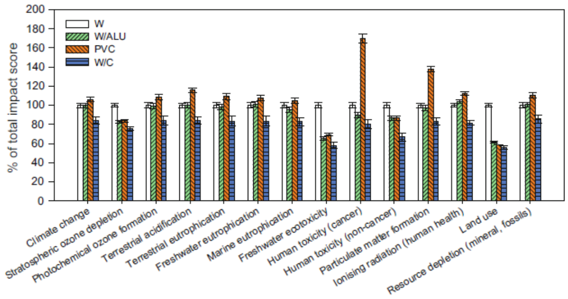
The end-of life of products and materials must be considered in order to assess the impact of the reference product when its service life end; the main issues considering this stage concern the uncertainty related to the impact for new or less known materials and to the various scenarios available for the end-of-life of all the components. Each of these indeed can have several possible scenarios. It is therefore interesting to understand how these aspects were addressed.
Sirvent et al. includes the only the auto-responsive VO_2 film and considers it to be easily detachable from the window surface, which is realistic given the application considered; however, the layer is treated as an inert waste, choice that is probably coherent for the considered impact indicators (Energy demand and CO_2) but that would probably be likely too optimistic if other EnICs were considered.
The other studies, being focused on static windows, address several known materials. Some papers account for different end-of-life scenarios for the window components, usually recycling, incineration and landfill; some make use of data related to their geographical scope, such as regional averages (Phillips et al. 2020), possibly from governmental institutions(Pomponi et al. 2016; Owsianiak et al. 2018), while others consider more generic data, mainly form regulations (Tushar et al. 2022; Azari 2014). In one study, only one end-of-life scenario is chosen for each component or material (Elkhayat et al. 2020) while others don't specify in a clear manner what choices were made in this regard (Feehan et al. 2021; Citherlet et al. 2000).
However, Owsianiak et al. point out how disposal has a limited importance on total impact, but this condition could change if the impact of operational energy will be reduced in future due to technological advances in the energy supply.

Uncertainty in LCA

Even though uncertainty of result is a very significant aspect of LCA and should be accounted for (International Organization for Standardization 2006; Hauschild et al. 2018), most papers actually avoid any numerical consideration of uncertainties, either by just mentioning their existence (Sirvent et al. 2022; Megange et al. 2019; Elkhayat et al. 2020; Phillips et al. 2020), or by completely neglecting them (Azari 2014; Pomponi et al. 2016; Feehan et al. 2021; Citherlet et al. 2000).
However, few papers address the issue of uncertainty more clearly: in their regression model, Tushar et al. also implement uncertainty calculation; this focuses specifically on the energy demand of the building through a Monte Carlo simulation, even though the procedure is not explicitly discussed.
Owsianiak et al. , instead, carry out a Monte Carlo simulation based on four parameters; these were chosen through local sensitivity analyses and the calculation of normalised sensitivity coefficients, used to determine the magnitude of the parameters' perturbation effect on the variation of the Impact Scores for each category, for the three chosen scenarios. The parameters' uncertainty distribution is normal, but the log-normal is suggested too. The global uncertainties were then calculated and represented through whiskers in the final environmental profiles, that compare the three scenarios for normalised referring to the baseline (see figure 2.7. Moreover, Owsianiak et al. specify that local analyses were carried out only on foreground processes and assert how the uncertainty of the results is increased by the choice of neglecting the uncertainties of background processes and those related to characterisation and normalisation factors.

Impact category	Unit	Impact score (95% probab
		W
Climate change	kg CO_2 eq.	1162 (1134–1189)
Stratospheric ozone depletion	kg CFC-11 eq.	1.9e−5 (1.8e−5–1.9e.5)
Photochemical ozone formation	kg NMVOC eq.	1.59 (1.55–1.63)
Terrestrial acidification	AE	2.00 (1.95–2.04)

(a) Results as displayed by Owsianiak et al.



(b) Environmental profile with uncertainties by Owsianiak et al.

Figure 2.7: Example of the final outputs of an LCA study, based on the work of Owsianiak et al. (2018)

2.2.2. The life cycle of a PSW

As aforementioned, a Passive Smart Window is a transparent technology that incorporates an Auto-Responsive layer and is very similar in structure to a static window: it doesn't require any external structure or substructure, as would double skin products, or electronics systems, as would active systems. The main difference lies in the build-up of the glazing, thus in the AR layer and in how this is integrated in the glazing itself. Given the strong similarities between static windows and PSW, the usual life cycle of a static window system will be described and later the possible differences will be highlighted.

Static Window Life cycle

This description is based on the common practice for windows life cycle in Europe and is illustrated in figure 2.8.
The first step consist in the production, thus the fabrication of the window. This starts with the supply of the main components of the glazing; the static glazing considered is a laminated DGU (double glazing unit) with low emissivity coating, thus the needed components three glazing panes, one internal and two external, a laminating interlayer and the liquid low-ε coating sufficient to coat one surface. First of all, the two panes are laminated with interlayer, then the internal pane is coated on one face (the considered coating is a solar control coating applied offline).
Once the panes are ready, the glazing is produced: the panes are cut, cleaned, sealed to the spacer by adding the sealant and finally gas is injected in the cavity.
The frame is then cut and assembled around the glazing. Once ready, the window is protected with a packaging and delivered to the building site, where it is located in the wall gap by mean of a crane.

The window operates for its whole service life, without specific need for maintenance besides cleaning, and affects the indoor climate of the room, due to the thermal losses and solar gains; at the end of its service life, it is removed from the wall, separated from the other wastes and collected with flat glass wastes. It is then transported to the waste processing site, where the frame is removed.
The glazing either goes to landfill or is crushed by hammers so that the glass shards detach from the PVB layer. The cullet, thus the waste glass, enters the recycle process: it is then cleaned from most of the impurities, it is sorted according to its quality and it is sent to different facilities, depending on its future use: the highest quality is used for new flat glass, while lower quality glass is used for glass envelopes or insulation product; only small percentages are usually discharged and sent to landfill. When the recycled cullet is remelted in the furnace, the coating that was applied to it evaporates, not affecting the new glass batch quality. The PVB layer is usually too contaminated with glass to be reused, but in some cases it can be recovered and recycled or incinerated for heat recovery, finally sending the ashes to landfill.

Passive Smart Window Life cycle differences

Little information could be found on the Life Cycle of the Passive Smart Window, mainly because of the lack of full assessments of these products and their currently reduced market presence. Most of the researchers who actually developed an Auto-responsive layer made a flexible film that was then attached to the indoor face of an existing window; this solution however doesn't sound realistic in terms

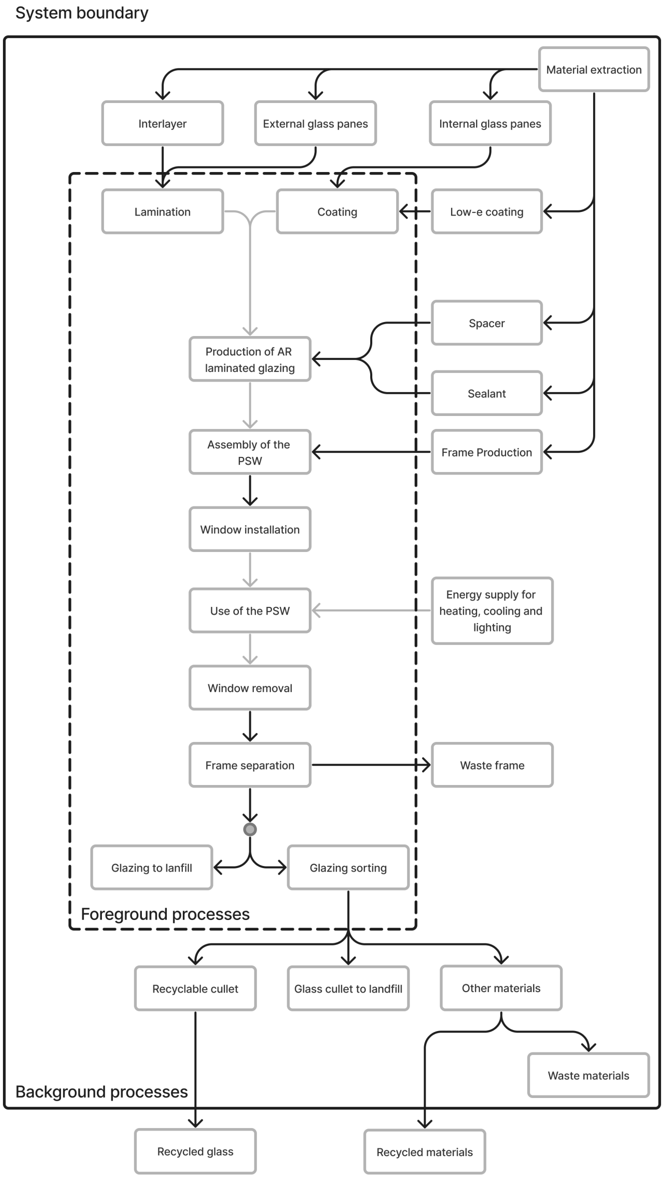


Figure 2.8: Project system for a static window. The black arrows indicate that transport should be considered. The box with a continuous edge defines the system boundary, excluding the recycling processes, while the box with the dotted highlights the foreground processes

of industrial development since it would expose the layer to the indoor environment. However, the supply of the layer reagents and the production of the layer would have an impact that is necessary to estimate. In addition, the End-of-Life of the PSW is very uncertain and would depend on the method used to integrate the layer in the glazing; the presence of the layer on the surface of the glass or within it could affect, probably increasing, the impact of the glazing. Even though Sirvent et al. assumed the layer to be detachable and considered it inert waste, more precise considerations and scenarios should be made. The possible systems to integrate the AR layer in the PSW and the consequent End-of-Life scenarios need to be formulated and analysed with more consistency. In addition, the lifespan of the AR layer may have a major impact if shorter than the lifespan of the glazing: in that case, it would require the replacement of the layer, if the operation is doable, or, more likely, the replacement of the whole AR glazing.

2.3. Literature Review: Energy Simulation

The main reason for interest of Passive Smart Windows is their influence on the operational energy use of the building they are applied in; both the academic world and in the industry focus indeed on their capacity to control the incoming solar radiation. Therefore, it is necessary to account for this effect in the LCA as well. However, the operational energy use depends on the energy demand of the space the window is applied to, thus depending on the building itself. This is a relevant complication, since it requires to include a context to the window application, with all the correlated parameters.
In order to understand what parameters are needed and how to characterise them, a second literature review was made, by researching on Scopus; since the improvement of thermal and optical properties is the main field of research for PSW, it was easier to find strongly correlated studies that analyse how the effect of PSW on the building energy demand. The review focused on the following categories of information and assumptions:

1. Software and climate data
2. Building model: typology and size, modelling of its envelope and dimensions of the window
3. Window characterisation: glazing build-up, transition behaviour and comparisons considered
4. Internal loads and indoor climate regulation: HVAC system and settings, occupancy and lighting

The main findings are reported in table 2.6 and following explained.

2.3.1. Software and climate

Software

The calculations of buildings' energy demand are most often carried out through energy simulation software. Several options are available but, as shown by figure 2.9, the great majority of the studies made use of EnergyPlus (Costanzo et al. 2016; Aburas et al. 2021; Salamati et al. 2019; Arnesano et al. 2021; Haratoka et al. 2023; Warwick et al. 2016; Nicoletti et al. 2022) or of a plug-in based on the same software (Kragt et al. 2022; Y. Zhang et al. 2022). EnergyPlus is indeed a worldwide diffused and well-established free software developed by the U.S. Department of Energy (DOE); it is also implemented in several design software, so it is easily integrated into the design process if needed. Tällberg et al. make use of IDA ICE but, as pointed out by the author, this is due to its popularity in the Scandinavian area, where the study is conducted. Ye et al. instead uses BuildingEnergy, a self-developed software validated by ANSI/ASHRAE Standard 140-2004 .

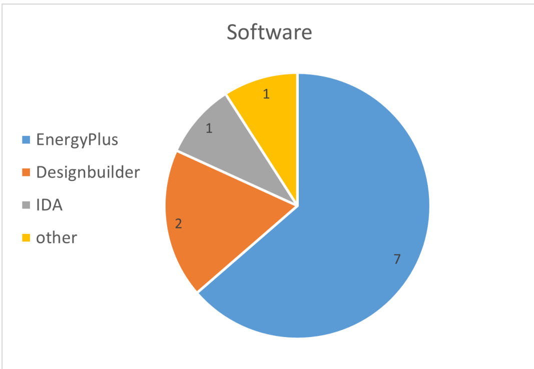


Figure 2.9: Software used by papers in LR

An interesting discussion about the suitability of BPS (building simulation software) for the modelling of Smart Windows was also found (Favoino, Giovannini, et al. 2017): this confirms how EnergyPlus8, was the most flexible tool available at that time of the study (2015) for the modelling of Smart Windows, both passive (TC and PC) and active (EC). Besides giving specific indications on how to practically model these technologies in the software, Favoino, Giovannini, et al. point out several limitations. The missing features that are most relevant for this study's scope are the possibility to model the response of the PSW towards different frequency bands, such as distinguishing between τ_{vis} and τ_{NIR} , the implementation of the hysteric properties of these materials, the implementation of angle dependency of their reaction to the stimuli and the effecting modelling of their time response. However, it is relevant to point out that since this study, which was conducted in 2015, EnergyPlus released new versions of the software, EnergyPlus9, EnergyPlus22 and the last EnergyPlus23, all with several intermediate updates. At the current date, the most recent version is EnergyPlus23.2.0 (National Renewable Energy Laboratory (NREL) 2023).

Table 2.6: Literature review for the energy simulation of PSW

Study	Num	Type	T_c in transition	Model size (m)	Timestep	Benchmark	Indoor T range	COP_c	COP_h	Heating type	Air flux (h^{-1})	Occupancy Schedule
Costanzo et al. (Costanzo et al. 2016)	#1	TC	Lower value of range	Building	N/A	DGU	20 - 26°C	N/A	N/A	air	0,3 (infiltration)	9 to 18; 5 days a week
Aburas et al. (Aburas et al. 2021)	#2	TC	mid value of range	5 x4 x 3	15 min	DGU and Low-e	21 - 24°C	3	3	N/A	N/A	8 to 18; 5 days a week
Salamati et al. (Salamati et al. 2019)	#3	TC	lower value of range	5 x 5 x 3	N/A	DGU	20 - 26°C	N/A	N/A	N/A	1,44 (ventilation)	all day
Arnesano et al. (Arnesano et al. 2021)	#4	TC	mid value of range	8 x 6,2 x 2,8	10 min	VGU (and DGU)	21 - 26,7 °C	1	1	air	0,24 (infiltration)	ASHRAE
Ye et al. (Ye et al. 2014)	#5	TC	41,3°C	4 x 3,3 x 2,8	N/A	”ordinary glazing”	N/A	local rule	local rule	air and gas	N/A	N/A
Haratoka et al. (Haratoka et al. 2023)	#6	TC	25, 35 and 45°C	6 x 5 x 3	N/A	DGU	N/A	N/A	N/A	air	N/A	ASHRAE
Kragt et al. (Kragt et al. 2022)	#7	TC	mid and max value of range	5,4 x 3,6 x 2,7	N/A	DGU	20 - 25,5 °C	gas	1	2,5	1,48 (ventilation)	Office_ OpenOff_Occ (software)
Y. Zhang et al. (Y. Zhang et al. 2022)	#8	TC	25	Building	1 min	DGU and Low-e	21 - 24°C	electric	1	1	N/A	8 to 17; 5 days a week
Warwick et al. (Warwick et al. 2016)	#9	TC	20,25,30,35	6 x 5 x 3	N/A	DGU	19 - 26°C	N/A	N/A	N/A	1,85 (ventilation)	8 to 18; 5 days a week
Nicoletti et al. (Nicoletti et al. 2022)	#10	PC	between 50 and 500 W/m^2	4 x 4 x 3	10 min	DGU	20 - 26°C	3,5	3	air	N/A	9 to 13, 15 to 19; 5 days a week
Tällberg et al. (Tällberg et al. 2019)	#11	TC and PC	TC: min and max	8 x 6 x 2,7	N/A	DGU and Low-e	20 - 25°C	1	1	electric	no	7 to 17; 5 days a week

Climate

About the climate data, the analysed papers made different choices about the locations, often choosing at least one location close or corresponding to the institution where the study was made; this is in some cases motivated by the fact that experimental measurements are performed in order to validate the model. More relevant is the fact that most of studies simulate the behaviour of the technology in multiple locations with different climates, usually 3 locations with different average humidity and temperature; these were sometimes in the same country (Ye et al. 2014; Haratoka et al. 2023), in the same continent (Costanzo et al. 2016; Aburas et al. 2021; Arnesano et al. 2021), or around the whole world (Y. Zhang et al. 2022; Kragt et al. 2022; Warwick et al. 2016; Tällberg et al. 2019). Anyway, the intent of the authors is usually to show the different effect of the analysed PSW according to the change in radiation and outdoor temperature, identifying the climate type where these technology would be more effective and to understand how the location affects the energy demand, always observing significant differences.
Nicoletti et al. use only one location since they aim to calibrate their model to the experimental test cell built, while Salamati et al. consider only the climate of Tehran to focus on the comparison of the PSW with three types of static glazing. The locations are shown in figure 2.10

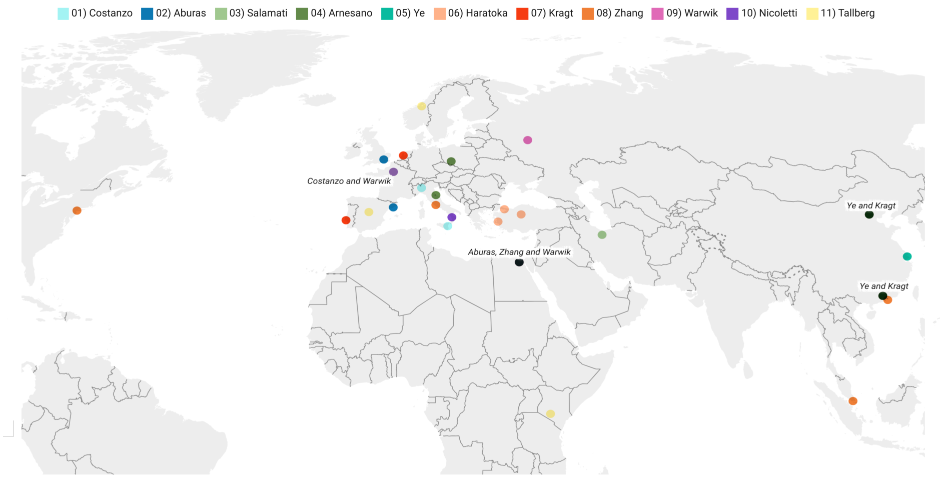


Figure 2.10: Locations from the studies of the Literature Review on energy simulation

2.3.2. Building and envelope characteristics

Use destination and model type

Most of the considered studies apply the PSW to offices (figure 2.11), which could be motivated by the higher standardisation of the needs and the higher regularity of their occupancy schedule, due to the predictability of the activities of offices. Most offices are modelled as a box provided with an exposed facade with one window, while all other surfaces have adiabatic properties (Aburas et al. 2021; Kragt et al. 2022; Warwick et al. 2016; Tällberg et al. 2019), or are very well insulated (Arnesano et al. 2021; Haratoka et al. 2023; Nicoletti et al. 2022); some studies instead model a small building (Costanzo et al. 2016) or an area within it (Y. Zhang et al. 2022), exposed to the outdoor climate on in all sides.

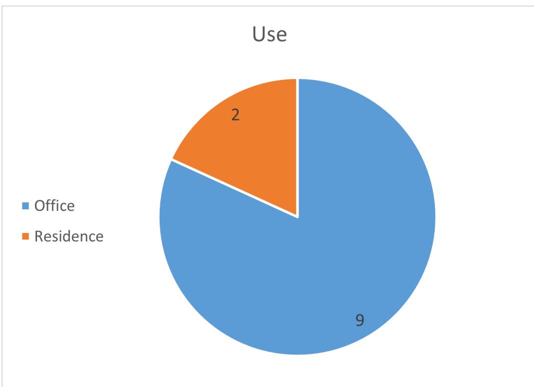
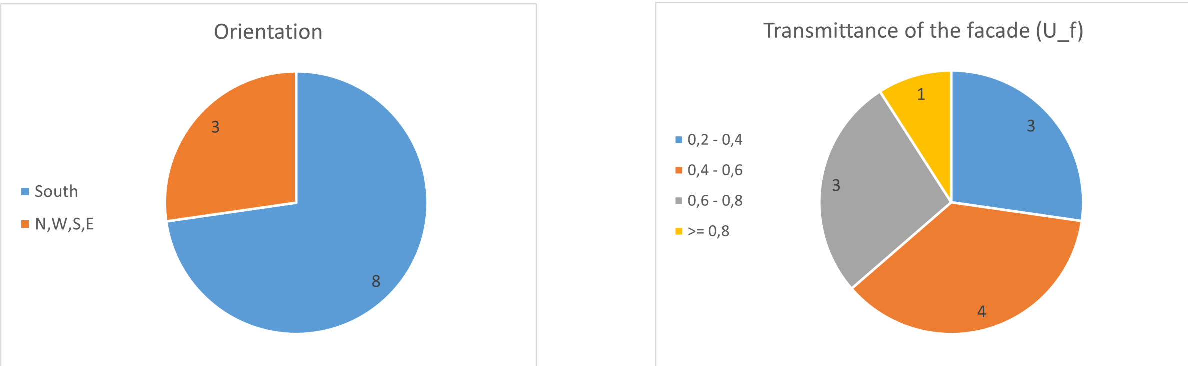


Figure 2.11: Use of the building in Literature Review

Salamati et al. and Ye et al. state to be simulating a residential space, but their characteristics are the same as the adiabatic box offices of the other studies, both for dimensions and internal loads, which include stable presence of occupants and equipment.

Building orientation and envelope properties

In order to simulate the energy demand of the conditioned space, the properties of the envelope need to be defined. All the studies need to define the thermal transmittance of the opaque facade U_f (figure 2.12b; this mainly ranges between a minimum of 0,25 W/m^{2}K (Kragt et al. 2022) and 0,8 W/m^{2}K (Aburas et al. 2021), with most of values between 0,4 and 0,6 W/m^{2}K. When considering box offices, no other exposed walls are considered and all the other indoor surfaces are considered to be adjacent to conditioned spaces with the same indoor temperature T_i and, consequently, indoor walls, ceiling and floor are assigned as adiabatic. Thus, in these cases, U_f is particularly important since it is the only exposed surface besides the window.



(a) Orientation of the building

(b) Transmittance of the opaque facade

Figure 2.12: Facade properties in Literature Review

As illustrated in table 2.7In the other cases, each exposed surface must be assigned with a thermal transmittance too. The U of other exposed walls, or external walls, can be defined in two different ways: when a full building is considered, the external walls are part of the facade and therefore have the same transmittance U_f, while if study make use of a test cell the external walls are characterised by a lower U_e, around 0,1 W/m^{2}K (Nicoletti et al. 2022). In these cases it is also necessary to define the properties of ceiling, U_c, of the floor U_g and, in case of full buildings with distinctions between the indoor zones, of the internal walls, U_i.

When used, U_u is 0,6 /m^{2}K (Haratoka et al. 2023), while U_c is lower, usually 0,7 and 0,4 ^{2}K. If there is a distinction between external walls and facade, as Nicoletti et al. do, U_e is lower, around 0,1 W/m^{2}K. The dimensions too depend on the specific study: these can be the same of a test cell (Nicoletti et al. 2022) or a real office (Costanzo et al. 2016) if the simulation is compared to measurements. Some others use standard models provided by the software or by governmental organisations (Salamati et al. 2019; Y. Zhang et al. 2022), but most use just rectangular office spaces without specifying in detail the origin of those dimensions (Aburas et al. 2021; Haratoka et al. 2023; Warwick et al. 2016; Tällberg et al. 2019) The box dimensions show variation, falling within reasonable ranges: the width varies from 4 m to 8 m, the depth ranges from 3,6 m to 6 m, and the height spans between 2,7 m and 3 m.
In some cases (Kragt et al. 2022), especially when a whole building is considered (Costanzo et al. 2016; Y. Zhang et al. 2022), PSW are placed and simulated on all orientations, usually to identify which one gives the highest improvements in terms of savings and or comfort. All the other simulations, instead, place the window on the south wall, as shown in figure 2.12a; the higher exposition to the sun of this orientation makes it the one that provides the most solar gains and, consequently, the most visible variations in terms of heating and cooling loads.

Window and frame dimensions

The presence of the window determines solar gains through the facade and an increase of its thermal losses compared to an opaque wall; however, the impact of a window on the thermal balance of the indoor space strongly depends on the portion of the of facade that is occupied by the window itself, thus Window-Wall-Ratio (WWR). It is therefore relevant to see what choices were made by the previous

Table 2.7: U values for different model surfaces in the analysed studies, expressed in W/m^{2}K. The values marked with (*) were calculated manually from the data provided. The work of Ye et al. is excluded since it didn't report any data on the envelope.

Surface	Office box	Exposed cell	Building
Facade - U_f	0,75 (Aburas et al. 2021), 0,4 (Salamati et al. 2019); 0,25 (Kragt et al. 2022)	0,52 (Nicoletti et al. 2022) ; 0,51 (Tällberg et al. 2019); 0,6 (Haratoka et al. 2023)	0,8 (Costanzo et al. 2016); 0,38(*) (Arnesano et al. 2021); 0,49(*)(Warwick et al. 2016)
External walls - U_e	N/A	0,11 (Nicoletti et al. 2022)	*equal to* U_f
Internal walls - U_i	*Adiabatic*	N/A	2,04(*) (Warwick et al. 2016)
Floor - U_u	*Adiabatic*	0,6 (Haratoka et al. 2023) ; 0,1(Nicoletti et al. 2022); 0,03 (Tällberg et al. 2019)	0,44(*) (Arnesano et al. 2021); 1,74(*) (Warwick et al. 2016)
Ceiling/Roof - U_c	*Adiabatic*	0,4 (Haratoka et al. 2023); 0,11 (Nicoletti et al. 2022); 0,32 (Tällberg et al. 2019)	0,7 (Costanzo et al. 2016); 0,26(*) (Arnesano et al. 2021); 2,55(*) (Warwick et al. 2016)

studies and what was the motivation for those. This concerns both the values chosen for the WWR and the other parameters the window area can be connected to, especially concerning the space energy demand. Indeed, there is not a perfect way to determine how the dimensions of a window influence the energy demand behind the facade, even though several studies have been carried out about this. The WWR is the most considered parameter, but the relation between the window area and the volume of the room or its depth, for example, are other factors that influence the energy demand of the room.
As shown in figure 2.13, the majority of the studies used a fixed value of WWR between 33% and 60%, determined through the indication of ASHRAE standards (Aburas et al. 2021; Haratoka et al. 2023; Y. Zhang et al. 2022; Tällberg et al. 2019) , which they often use also for the modelling of the building geometry and loads in terms of occupants. Indeed, the ASHRAE (American Society for Heating, Refrigerating and Air-Conditioning Engineers) provides extensive standards for the building sector and building prototypes (U.S. Department of Energy (DOE) n.d.) and is consequently quite popular.

Some studies make use of real measurements, such as Costanzo et al., using a WWR of 43 % taken from their own office reproduced in the energy model, or Nicoletti et al., using the dimensions used in their experimental test cell, for a WWR of 15%. Warwick et al. uses a WWR of 99% as "representative of modern office blocks", while the other papers do not provide specific references or motivations for their choice, which indeed range widely: 24% (Ye et al. 2014), 25% (Salamati et al. 2019), 60% (Kragt et al. 2022), 83% (Arnesano et al. 2021).
The area for the window usually coincides with the area of the wall opening,since most of the studies do not seem to consider any window frame; indeed, very few studies describe, show or mention the window frame. However, they all use aluminium frames; some provide the frame fraction, 15% (Nicoletti et al. 2022), while some (Costanzo et al. 2016; Tällberg et al. 2019) also provide the frame's U values, 2,9 W/m^{2}K and 2 W/m^{2}K , and emissivity, 0,837.

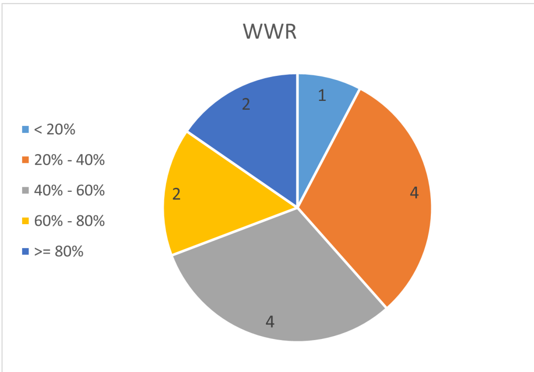


Figure 2.13: Window-Wall-Ratio in Literature Review

2.3.3. PSW characterisation

This section of literature review focuses on how these technologies have been modelled and characterised in the studies, rather than on the specific values of the PSWs tested. The specifics of the PSW depend on the product to be tested, but the subject of interest is how to model the transition of the product's properties, determining the mathematical relation between the ON/OFF states and the stimuli, the speed of response and how to implement these aspects in the most effective way in the model.

Glazing build-up in the model

First of all, it is relevant to see what choices were made in terms of integration of the AR layer in the glazing build-up and how it was modelled in the simulations. All the considered studies simulated a DGU with the added AR layer. Sometimes, it is specified how the PSW is also provided with a low-e coating, placed on a different glass face than the AR layer (Aburas et al. 2021; Y. Zhang et al. 2022).
As for figure 2.14, the thermochromic layer is either a coating, applied directly on the outer glass pane (Aburas et al. 2021; Salamati et al. 2019; Haratoka et al. 2023; Y. Zhang et al. 2022), an interlayer laminated between the outer panes of the glazing (Tällberg et al. 2019) or a coating applied on a PET substrate, later attached to the glazing (Costanzo et al. 2016; Arnesano et al. 2021; Ye et al. 2014; Kragt et al. 2022). No difference in efficacy between these applications was reported, thus the choice on one option among the others in each study is assumed to depend only on the specific material used for the technology. In the case of the photochromics instead, both studies (Nicoletti et al. 2022; Tällberg et al. 2019) consider an adhesive film attached to the glazing. However, the AR layer is always treated as part of the outer glass pane of the glazing, both for Thermochromics and for Photochromics, and it is apparently assumed not to be influenced by the other components of the window.

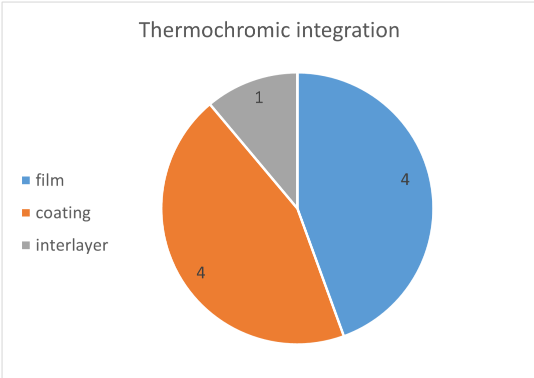


Figure 2.14: Integration of Thermochromic in the build-up

Transition modelling

The transition between the clear (Off) and the tinted (On) state is gradual and does not occur at a specific value of the stimulus. The transition of thermochromics does not occur at the Critical Temperature or Transition Temperature, T_c, but within a range around it (Costanzo et al. 2016), so around a temperature range. For Photochromics, the same can be said about the solar radiation intensity. This means that the PSWs assume intermediate optical properties while transitioning from a clear to a tinted state and vice-versa; these intermediate states determine the solar gains that the PSW allows in the indoor space and thus must be modelled properly.

Thermochromics react to their own temperature and the analysed studies assume this to be the same as the temperature of the outer layer of the glazing, due to the position of the AR material in the outer pane. The AR material is thus assumed to change behaviour when it reaches the T_c, which is defined sometimes as the lowest limit of the transition curve and some others as its middle point. Some studies avoid any explanation concerning the transition of the thermochromic material, reporting only the T_c, with values spanning between 20 and 45°C, and avoiding any observation on the transitional range (Aburas et al. 2021; Salamati et al. 2019; Ye et al. 2014; Haratoka et al. 2023; Y. Zhang et al. 2022); moreover, in the study by Y. Zhang et al., the thermochromic technology is modelled only in the clear and tinted state, essentially assuming an immediate switching

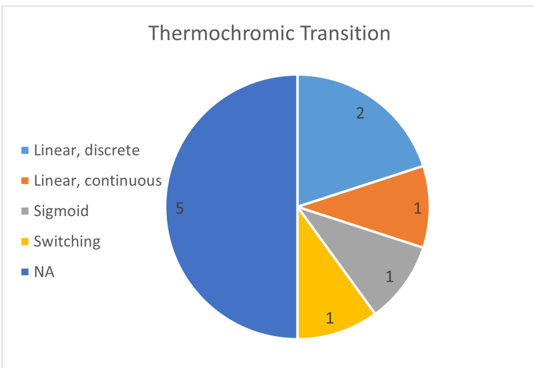


Figure 2.15: Modelling of properties transition in Literature Review

without any proper transition. However, from the rest of the literature it is evident how important it is to define the temperature transition range, either by giving its two extreme values or by providing its width and one value, usually the middle or lower one. The temperature transition in the studies was modelled with two different approaches;

one is a linear correlation between the clear and tinted state: this is the simpler approach to implement and can make use of one or more intermediate states (Costanzo et al. 2016; Kragt et al. 2022) or of the interpolation of temperature T and transmittance τ (Tällberg et al. 2019), thus assuming a continuous linear correlation. The alternative approach consists in approximating the transition to a sigmoid curve (Arnesano et al. 2021), which provides a smoother shift between the transition state and the stable states (Fig: 2.16). However, in the sigmoids developed by Arnesano et al. the slopes are arbitrary and no correlation is provided between the width of the temperature transition range and the slope.

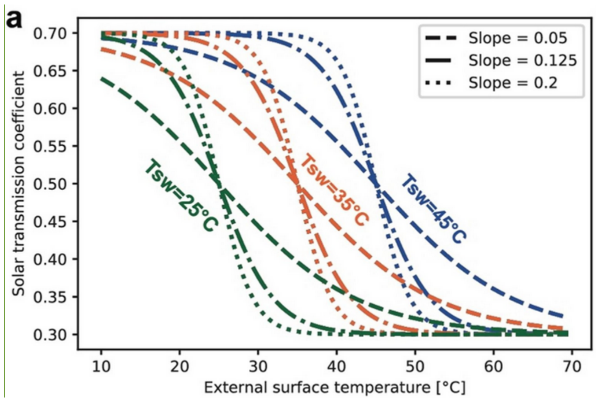


Figure 2.16: Sigmoid transition curves of τ_{sol} , with different critical temperatures (Tsw) and slopes (Arnesano et al. 2021)

Most of the papers, either explicitly or implicitly, neglect the effect of the hysteresis of the thermochromic materials; the only exceptions are Aburas et al., who mention a 4 degree hysteresis, without specifying how this is implemented, and Warwick et al. , who actually focus on the optimisation of the hysteresis cycle and observes the higher efficiency of a narrow cycle; however, they don't make any observation or recommendation on realistic modelling of the hysteresis. However, the hysteresis is said not to have a meaningful impact on the energy performance of the glazing (Arnesano et al. 2021). In addition, none of the studies mentions the variation of the absorbance with the decrease of the transmittance.

Photochromics' reaction is instead triggered by the global solar irradiance incident on the material's surface. Few sources were found for this, but both describe the intermediate transition state with an linear correlation from a minimum of 50 (Nicoletti et al. 2022) or 100 W/m^2 (Tällberg et al. 2019) to a maximum of 450 W/m^2. Nicoletti et al. discretises the range in 9 steps , while Tällberg et al. uses interpolation, as for the Thermochromics. In both cases, the software doesn't provide a dedicated function to model the Photochromics' behavior in the window, but that is possible through macros. The issue of hysteresis is less relevant for this technology (Tällberg et al. 2019) and it is indeed neglected by both studies.

For both thermochromic and photochromic technologies, the reaction time of AR layer and the time step are assumed to be between 10 and 15 minutes, except for Ye et al., where the model assumes the AR material to switch from clear to tinted in 1 minute.

At the current date, EnergyPlus (National Renewable Energy Laboratory (NREL) 2023) has introduced a function to discretely define Thermochromics: the user can define a series of temperatures within the transition range and associate each of them to a specific glazing, with the properties of the thermochromic window for that temperature. There, transmittance and reflectance for NIR, visual and solar ranges can be defined. For each iteration, the program will take the temperature of glazing at the previous iteration and will choose the state of the window associated with to the closest temperature.

Benchmark technology and comparisons

All of the studies considered compare the one or more Passive Smart Windows to static windows, usually a DGU (Costanzo et al. 2016; Salamati et al. 2019; Ye et al. 2014; Haratoka et al. 2023; Kragt et al. 2022; Warwick et al. 2016; Tällberg et al. 2019), sometimes provided with low-e coating (Aburas et al. 2021; Y. Zhang et al. 2022; Nicoletti et al. 2022), or a more efficient VGU (vacuumed glazing unit) (Arnesano et al. 2021). To limit the comparison to the effects given by the Auto-Responsive material, the build-up of the reference and of the PSW glazing was always identical or very similar. In some cases, several types of PSW were compared, mainly varying a specific property, such as the T_c(Costanzo et al. 2016; Warwick et al. 2016) or the thickness (determining the optical spectrum) (Aburas et al. 2021). In the study by Tällberg et al., the TC and PC windows were compared to a static reference and to an Electrochromic window with different control strategies, so a dynamic alternative. Indeed, three different control strategies were defined for this active technology, based on the solar radiation, the daylight and the operative temperature. The radiation-based strategy is implemented with the same mechanism used for the photochromic, with a linear correlation between the solar radiation and the tinting of the glass; this strategy thus resembles the behaviour of the PSWs, especially of the photochromic. The daylight-based strategy activated the response of the electrochromic glazing when the indoor illuminance exceeded a threshold of 500 lux. Finally, the operative temperature-based strategy assumed the electrochromic to switch, becoming fully tinted, when a threshold is reached; that was defined as the 1°C below the cooling set-point.

2.3.4. Indoor conditions, loads and systems

The indoor conditions of the simulation, as the building model itself, depend on the study that is being carried out: when the simulation is applied to a known or existing space (Costanzo et al. 2016), the systems considered may be modelled according to those existent or designed for that space. If the simulated building is not specific, the services may be defined in a generic way, likely based on regulations or standards. Similar observations are made for internal loads, such as people and equipment, while some more attention is given to the lighting, especially for those studies whose scope includes indoor visual comfort (Costanzo et al. 2016; Aburas et al. 2021; Haratoka et al. 2023; Nicoletti et al. 2022).

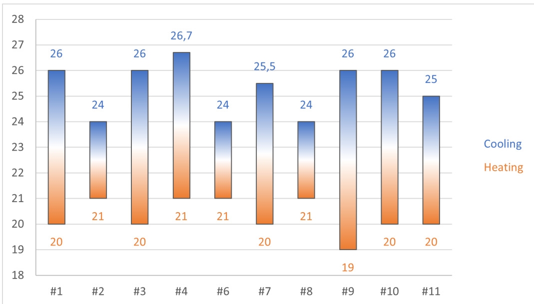


Figure 2.17: Set-points for heating and cooling

In general, all the sections related to the definition of the internal loads and to building services are explained quite quickly in all the papers, suggesting how their modelling has limited importance when the scope of evaluation PSW in comparison with other glazing technologies.

Indoor temperature settings and HVAC

The HVAC system and the corresponding set-points are usually based on the local standards or on modelling templates derived from the standards themselves. As for figure 2.17, cooling is always assumed to be an air system with set-point T_{cool} usually around 26°C, even though in some cases it is set slightly lower, between 24 and 25°C. The heating is mostly defined using an air system, with set-point T_{heat} usually around 20°C. Only Kragt et al. uses a gas powered system, due its implementations in the building model template used.
The performance coefficient of the HVAC systems determines the energy demand of the space: most studies use ideal systems, thus assuming COP of 1 for both heating and cooling. Only three instead use a realistic value(Aburas et al. 2021; Ye et al. 2014; Kragt et al. 2022), ranging between 2 and 5, usually taken from local standards. Both approaches can be considered correct as long as all the simulations compared are based on the same model. Air fluxes in the indoor space are often ignored, either explicitly (Tällberg et al. 2019) or implicitly (Aburas et al. 2021; Ye et al. 2014; Haratoka et al. 2023; Y. Zhang et al. 2022; Nicoletti et al. 2022). Only some studies consider a ventilation rate around

1,6 h^{-1} (Salamati et al. 2019; Kragt et al. 2022; Warwick et al. 2016) or air infiltration rate of circa 0,3 h^{-1} (Costanzo et al. 2016; Arnesano et al. 2021).

Occupancy

Among the heat gains an indoor space is subjected to, there are internal gains due to occupants and equipment. These depend mostly on the building use and, consequently, on its occupancy schedule; indeed, given that most of the studies consider office spaces, the occupant density is usually between 0,11 and 0,05 person/m^2 when specified, with a corresponding load of 120 W/person. The power density of the equipment ranges from a minimum of 150 W ($\simeq$ 3,1 W/m^2) to values of 11,77 W/m^2. However, these values usually derive from standards, mostly ASHRAE (Arnesano et al. 2021; Haratoka et al. 2023), or from schedules, implemented directly in the energy simulation program (Kragt et al. 2022). All studies consider an occupancy schedule between 7 or 9 in the morning until 17 or 18 in the evening, 5 days per week. The only exception is provided by Salamati et al., who assume a residential building occupied 24h a day all week.
The schedule is relevant to the overall energy demand since it does not only define the duration of the internal loads but it also defines when the HVAC system need to operate to keep the temperature within the comfort range and when potential active shading devices are in use. Nevertheless, this doesn't influence the functioning of the passive systems, including PSWs.

Lighting

The lighting system is supposed to compensate for the lack of proper visible light indoors for the users, so only when the building is occupied. PSWs affect the incoming radiation through the window and, even though they mostly focus on regulating the NIR spectrum, they affect the visible spectrum as well. Therefore, most of the studies assume the indoor lighting system to be activated when one or more sensors register an indoor illuminance lower than a certain threshold. Figure 2.18 illustrates how, in most of the cases, this threshold is 500 lux, while in some cases it is set at 300 lux (Costanzo et al. 2016) or 400 lux (Salamati et al. 2019). The sensors are usually positioned at the height of a working plane, so 0,8 m from the floor, at either 1 or 3 m from the facade wall, or in the middle of the room. In most cases, the lighting system is either active or inactive, with one exception by Tällberg et al., who assume a lighting system dimmed to compensate for the lack of indoor illuminance between 100 and 500 lux.

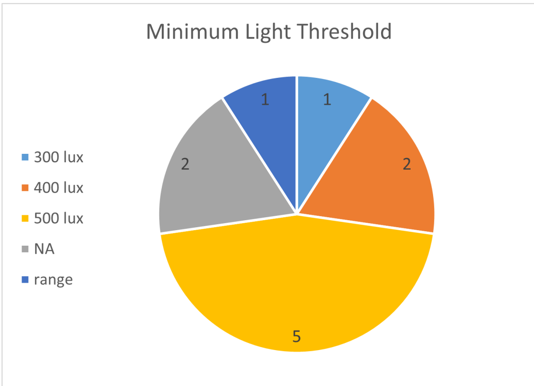


Figure 2.18: Minimum light threshold in Literature Review

The lighting produces internal heat load too, so its power density must be defined. This is usually given by the standards, depending on the lighting system's efficiency. LED systems are known to have a considerably lower energy dispersion and consumption compared to typical light bulbs, thus causing lower energy demand for the lighting and lower internal loads, with consequences on space conditioning.

3
Interviews

3.1. Introduction

In the literature review several examples of research papers on LCA of windows were analysed. However, these papers didn't provide all the information needed for the redaction of the framework. They couldn't fully clarify what is the End-of-Life of glazing, thus preventing them from properly modelling the impact of the End-of-Life of the windows. Aspects related to the use of PSWs were also unclear, such as how could the layer be included in the glazing's build-up, how would it be treated in the End-of-Life given the current infrastructure and what would be the possible impact. Finally, doubts remained about the application of the LCA approach to facade elements, especially concerning the consideration of the operational stage, the choice of a proper method, the evaluation of uncertainty and the weighting of the results.
Considering that these knowledge gaps were strictly related to the practice of LCA application, to the fabrication processes and to the industrial sector in general, it was decided to conduct a series of interviews with experts from the industrial sector itself. This would help to verify the validity of the assumptions so far developed for the framework, completing it with more information about the missing knowledge. The interview allowed to adopt different perspectives on the object of the research and to pose feedback questions in case of unexpected answers. Of course, the results of the interviews should be taken with caution since the involvement and the interest of the interviewee may induce biases . The questions were prepared to be as neutral as possible and, when there was the opportunity, a comparison of answers of different interviewees was made.
Given the time limitation, only a seven interviews were conducted; the interviewee were chosen from the different areas covered by the study, to get information on most of the topics that seemed incompletely addressed in the literature.
All the interviewees were given a introduction that would present the topic of the research and were provided in advance with the questions; to each interviewee, only specific sections were of the question list were asked, depending on their competence and on their availability. The introduction and questions are here reported, while the outcome of the interviews is presented in the next section.

Introduction for the interviewees

The aim of this study is to develop an LCA method about Passive Smart Windows (PSWs), thus windows that integrate an auto-responsive layer, capable of autonomously changing its optical and thermal properties due to the variation of stimuli of the outdoor environment. This definition, include mainly two technologies: thermochromic and photochromic glazing. These layers can be made of several materials: thermochromics (TC) can be made of VO_2 based nanocrystals (vanadium dioxide, usually doped with tungsten, titanium and other substances), liquid crystals, ionic liquids, perovskites and hydrogels. Photochromics (PC) instead are usually compounds based on noble metals, transition metal oxides (WO3, TiO2, MoO3, V2O5, Nb2O5) silica or organic compounds (fulgides, spiropyrans, spirooxazines, naphthopyrans, and azobenzenes). Electrochromic technology was considered as active and was therefore excluded from this study.

Studying these technologies, doubts arouse on PSW's production, concerning how the auto-responsive layer is or could be integrated in the glazing. In specific, it is this study's objective to understand the processes needed to do so, including what kind of machines would be used and to what current, more popular, production process these could be assimilated to, in terms of environmental impact calculations.
Secondly, the End-of-Life is even more uncertain, since the disposal of these technology has not been faced yet, in practice. In general, the questions concern the influence of the presence of the auto-responsive layer in the glazing, thus how would the integration of this layers affect the usual End-of-Life of windows and its components, and the environmental impact of the auto-responsive component itself. Again, it is important to find consolidated products and processes to be assimilated to.
To evaluate the impact of PSWs, a comparative LCA is made. The definition of the term of comparison or benchmark is part of the study itself. The idea is to compare PSWs with the current building element that they would replace so it was considered to choose a static window provided with dynamic shading. Therefore, the only difference between the PSW and the benchmark would be the dynamic component, thus the auto-responsive layer and the shading, and the rest of the build-up would be the same. However, the build-up remains relevant: it affects the results of the operational energy and the fabrication of the PSW, having consequences both on its production and on its End-of-Life.

Questions

1. **Window build-up and benchmark**
   - What is the most common build-up for glazing (curtain walls or windows) for office buildings?
   - What dynamic systems are preferred, from a performance point of view? Louvres, roller blinds, venetian blinds? Which systems are actually most frequently installed?
   - How are dynamic shading devices usually activated? Manually or automatically?
2. **Auto-Responsive layer**
   - Are the materials used for auto-responsive layer used also in other fields?
   - How would this layer be like? Would it need to be spread on a substrate? Does or can it need to be laminated? Can it be applied to glass directly?
   - Is there a wide range of methods for the production process of auto-responsive layers? What are these possible processes?
   - Are these processes comparable to other used for different materials? Do they require specific equipment?
   - What would be the compound impact at the product End-of-Life? Are the compound's emissions similar to those of its components?
3. **PSW Production**
   - How would you integrate an auto-responsive layer in the window build-up? Lamination, coating, adhesive film… What would motivate this choice?
   - How would that integration work, concerning the production processes of the element?
   - Would these processes be similar to those usually applied for static windows? What differences would they have in terms of machines, materials and energy needed?
     - In case of lamination, would that require more energy or additional materials?
     - In case of coating, would that be comparable to the typical coating method? If not, in what terms?
     - In case of adhesive film, at what point of the process would that be integrated? Could it be assimilated to other processes?
4. **PSW End-of-Life**
   - What's the usual End-of-Life of windows? Landfill, recycling, downcycling? What does it depend on?
   - What methods are commonly used to recover the post-consumer flat glass (e.g. laminated glass, coated glass)? Do they also allow to recover other components as well? How often are these systems actually used?

- What is the possible use of the glass recovered from lamination? Full recycle or only down-cycle?
- How could the integrated layer affect the End-of-Life of the window?
  - Would it affect the recyclability of the glass itself?
  - Would it be possible to retrieve it? And to recycle it?
  - Would it be possible to separate it from the glass?

5. **New section - PSW manufacturer**
   - What types of technologies do you produce? Thermochromic, Photochromic, Electrochromic? Any other? For how long have you been working with them?
   - How do you integrate the responsive layer in the glazing? (specifically Thermochromics and Photochromics)
     - Coating, lamination, adhesive?
     - Where is it located in the window build-up?
     - Do the replace low-e coatings or are thy additional features for the glazing?
     - What are the steps for the integration process?
   - How is the layer produced? What materials is it based on?
   - What is the lifespan of these dynamic glazing systems?
     - Is it different from static glazing?
     - How does the layer affect their lifespan of the whole product?
   - What are the possible failure mechanisms of these layers (Thermochromics and Photochromics)?
     - Do they just stop reacting to the stimulus?
     - Do the $T_{critical}$ or $\Delta\tau_{sol}$ change in time?
     - Do they have an ununiform tint? Else?
   - What is the End-of-Life of this products?
     - Can these windows be recycled?
     - Can the layer be separated from the rest of the glazing when it is dismantled?
     - Do you know already the impact of these products?
     - In case what life cycle stages did you consider?

6. **New section - LCA practitioners**
   - How do you deal with missing data?
     - What sources do you trust to get new data (e.g. research papers)?
     - How do you derive the impact of a new process from a similar known one?
     - How do you model new End-of-Life processes?
     - How would you do that foe Auto-Responsive materials?
   - How do you deal with multiple scenarios, especially for end-of-Life?
     - Do you choose only one? Do you calculate several and compare them?
     - When considering recycling, where do you set the system boundary?
   - How do you consider uncertainty?
     - At what stage do you consider it? For which processes?
     - What sensitivity analyses do you carry out?
     - How do you estimate the values for the uncertainties you use?
     - What is the purpose of Monte Carlo simulation and when is it meaningful to use it?
   - How do you calculate for transportation when you don't have specific locations to consider?
     - Do you assume specific locations? Do you make an average?
   - How do you deal with the operational energy in the LCA?
     - Would you consider the whole energy demand of a building/room as operational energy or just part of it?
     - Would you use the window as a functional unit, or the whole building/envelope?
     - Would you integrate it in the LCA or compare Operational vs Non-operational impacts?
   - How do you normalise your results?
     - How do you choose the reference population?
     - When do you weigh the results? Based on what sets?
   - What do you base your methodology choices on?

- How do you choose database and software for an LCA?
- How do you choose your LCIA method? And normalization and weighting sets?

• How would you account for the replacement?

- How would you estimate the replacement rate?

3.2. Interview outcome

The content of the interviews was summed up based on three main topics:

1. Flat Glass End-of-Life
2. AR material and PSWs
3. Glazing LCA

Each interviewees are listed in chronological order of their interviews, mentioning their role and the organisation they belong to:

A) Managing Director - Glass recovery and recycling foundation
B) PSW researcher - University and PSW Start-up
C) Sustainability leader - Facade contractor (NL)
D) Glass recycling manager - Glass recycling company
E) Company director - Smart window supplier
F) Innovation manager - Facade contractor (IT)
G) Sustainability consultant - Sustainability consultancy

The diagram 3.1 summarises how each of the interviewee contributed to the main topics listed.

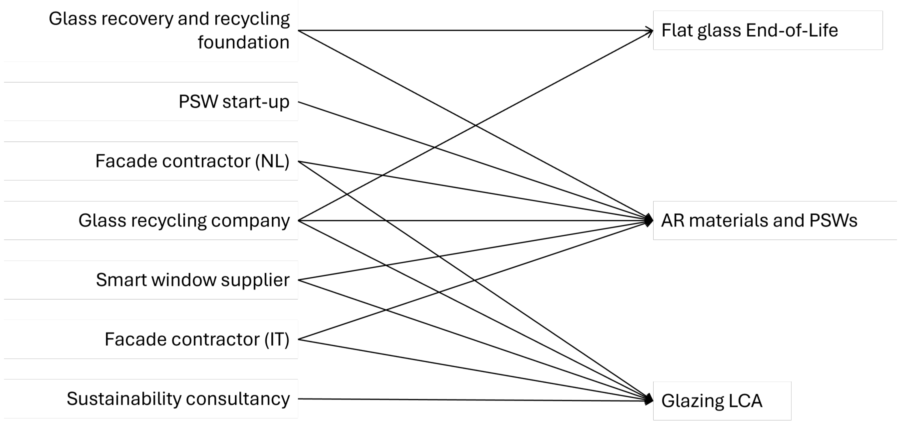


Figure 3.1: Contribution of the interviewees to the main topics the interviews

3.2.1. Flat glass End-of-Life

Flat glass recovery

The life cycle of flat glass needs a higher level of purity compared to common glass and thus needs to be separated with higher care. According to D, a glass recycling company, when addressing flat glass recycling it is important to distinguish between waste from flat glass manufacturing (PIR or Post-Industry Recycling), such as fragments resulting from the cutting of the panes or waste discharged because of impurities, or waste from the building sector (PCR or Post-Consumer Recycling), so flat glass used in buildings at the end of its service life. In some countries, such as France and the Netherlands, a recovery system for PCR was set up in the last decades, aiming to collect the flat glass and to introduce it again in the value chain. According to D, in these countries, the building sector and the

legislation are moving towards the separation of flat glass from other construction wastes, so to limit as much as possible contamination with other materials. Moreover, flat glass PCR includes also all the flat glass used for greenhouses and indoors, so from tables, showers and fridges. According to A, a foundation operating in flat glass recovery and recycling, the Netherlands have the highest rate of flat-glass recycling per inhabitant, collecting around 80% of the PCR in the country, around 89.000 tons, while the rest goes to landfill as construction waste.
As D points out, there are alternatives to recycling, first of all, the reuse of glass; this is significantly less impacting but it is still hard to implement for glazing. It is suitable for glass envelopes, such as bottles, since they are easy to clean and collect, but it is hard to implement in the flat glass industry, due to high requirements in terms of performance and safety. Both A and D highlight how the recycled cullet is appealing to the glass industry: first of all, it decreases the need for raw materials since 1,25 tons of virgin minerals can be replaced by just 1 ton of recycled cullet in the melting batch. Secondly, according to D, the use of 10% of recycled cullet induces energy savings of around 2,5/3% of the total energy consumption for glass production.

Flat glass recycling process

According to the A, the collected flat glass is crushed and fragmented with specific machinery, that reduces it to cullet of small shards of maximum 5 centimeters. From the windows, only the frame is removed; the glazing is crushed with all its components, they will be separated later. There is no distinction between single panes, laminated glass or IGUs; spacers, sealant, and lamination interlayers are crushed too, but they will need to be removed afterwards. The recycling of laminated glass is an established practice that has been done for at least 10 years now. To better separate the polymeric interlayer from the glass shards, it is put in a rotating drum that crushes the shards even more, so to increase the amount of recycled glass.
D explained how the cullet needs to be sorted, removing the impurities and dividing it according to its quality. The contaminants that end up in the cullet may compromise the new glass batch, especially for flat glass, where a small contaminant can damage a large amount of glass produced in the continuous production line. Metals are removed with two different methods: ferrous metals are removed through magnets while non-ferrous metals are removed through Eddy current. Light-weighted materials, such as paper and plastic, are removed by suction. Finally, optical sorting is by far the most important sorting process, according to D. This process makes use of optical sensors: the cullet runs over a belt and, at the end of it, shards and contaminants fall; the camera system distinguishes contaminants from the glass and shoots them out, removing them from the cullet. This process can consist of several steps based on different technologies. This process eliminates fragments of concrete and CSP (ceramic stone and porcelain) which could not be eliminated otherwise. When shooting out the contaminant,s also several glass fragments are removed, approximately 8 for each shoot; thus, a higher use of optical sorting decreases the yield of the recycling, eliminating some clean glass as well. After the optical sorting, the cullet is sorted and directed to new production cycles. In the Netherlands in 2022, according to A, 91,3% of the collected mass of flat glass waste went back into the glass industry; specifically, 57,2% was used for glass envelopes and 24% for glass insulation, while 9,3% was re-accepted in flat glass production; A specifies their objective is to reach 20% of cullet redirected in the flat glass industry. Only 1% of the material went to landfill, while the remaining 7,7% consisted of non-glass material, such as metal, films, CSP and wood. However, according to D, PCR glass is often too contaminated to be reintroduced in the cycle for flat glass, mainly due to the improper separation on the demolition site. D asserts that most of the cullet recycled in flat glass comes from PIR, excluding the windows at their end-of-life. Their data though refer mostly to the French context, while for the Netherlands they confirm the data provided by A, with a recycle rate of PCR flat glass slightly below 10%.

Impact of glass coatings

According to both A and D, common glass coatings are not considered to be a problem by the glass producers, since the materials of the coating evaporate at the melting temperature of 1300 °C and do not affect the batch itself. A asserts that the low percentage of recycled cullet in the batch makes any possible effect of the coatings irrelevant but D warn about a possible issue: in their opinion, the gases coming from the melting batch already cause reactions within the furnace due to particular conditions given by temperature and gas pressure. Cold spots in the furnace are the most exposed to these conditions: the reaction between vapour and evaporated soda oxides, for example, can produce caustic soda, capable of damaging the reflective materials of the furnace. According to D, the glass manufacturers are not really aware of this issue and this could worsen with an increased percentage of recycled cullet or with new coatings.

3.2.2. AR material and PSWs

AR materials and production

B is a researcher who developed a photochromic window and is working on a thermochromic window as well. According to B's experience, most of the AR compounds used for photochromic are inorganic, mostly metal oxides such as silver oxides. For this technology, the oxide particles are embedded in a coating that is later applied to the glass. Their thermochromic technology is instead based on liquid crystals, thus are an organic compound. This material is also used for electrochromic technologies, where two electrode layers include the liquid crystals. Indeed, liquid crystals always need a substrates to encapsulate them due to their liquid physical state.
B affirms that AR materials are often produced as pigments, following some common steps. The first is a hydro-thermal reaction, which is quite energy consuming. The particles can the be embedded in a polymeric layer or in a coating. For the polymeric layer, the polymeric cullet which is melted and mixed with the particles, and is finally extruded to produce a film. For coatings instead, the AR particles are mixed in a solvent; the solution is later spread on the glass and cured at high temperatures in order to fix or eliminate the solvent. It was asked for the coherence of the AR production in the description given by Sirvent et al.; in B's opinion, the application of the coating on the glass surface can be considered to have a very low impact compared to the other processes, thus justifying the exclusion of its impact in the paper's calculation.

Static windows and PSW build-up

Before understanding how AR materials are and could be integrated in the glazing build-up, it was investigated what is the current practise for static windows. According to the facade manufacturer F, it is hard to define a typical glazing requested by the market. High-rise office buildings in the UK have a considerable request for TGU (triple glazing unit), mainly due to the lower U value, but DGU are still the most commonly requested glazing in the Italian and American market. F specifies how these demand may change depending of the size of the building, on its destination and on the local requirements for energy efficiency. F also states that integrated solutions for light shading are not really frequent, currently. Cavity integrated venetian blinds, external louvres and external shading are quite rare. Indoor blinds are the most used solution and are almost always needed to control glare; however, these are not provided by the facade contractor, since they are usually added in a second moment and can change with the user of the building. Integrated internal blinds are not requested by the market and so are not being developed by contractors.
Focusing on PSWs instead, B identifies three main options for the integration of the AR layer in the glazing build-up. The first option is a coating: the pigment is mixed with a solvent to make a solution, applied on the surface and dried. This face should be inside the glazing cavity, so to be protected from the external agents. According to E, this option is used only for Thermochromics.
The second option consist in using a film with embedded AR particles as interlayer of the laminated glass pane. F states how both glass panes need to be tempered for safety reasons; E confirms that, adding that this solution is mainly used with thermochromic windows and defining the glazing production process as similar to standard lamination. However, they add that this option could be used for Photochromics too.
The third option is to apply an adhesive film with embedded particles; E specifies that they use this option for Photochromics and that this layer is used mostly for refurbishment of static glazing. For this reason, this layer is applied to the face 4 of the glazing, thus leaving it exposed to possible damages from the indoor space.
E adds some information about PSWs: first, all the PSW need a low-e coating placed on face 3, especially Photochromics, while the UV protection would be provided by the PVB interlayer. Then E explains that both technologies can react in a non-uniform manner to the stimuli: if only a portion of the glazing is hit by the solar radiation, that portion will tint more than the rest of the glazing. Finally, E points out

that the two technologies have different reaction times: Photochromics react within few seconds from the UV impact on the window surface, while Thermochromics take between 5 to 10 minutes to react to the temperature variation.
The PSW's potential to control glare however is not clear: the PSW supplier E claims that PSWs with thermochromic interlayers can control glare since they reduce the τ_{vis} as well. However, F affirms that PSWs are unlikely to replace blinds, due to the lower flexibility in activation and that probably blinds would still be needed for office spaces.

Lifespan for LCA

In general, lifespan is difficult to be clearly defined since it varies depending on the local market, says F. In Italy, a building facade can last around 50 years, while the market in the UK and the Netherlands is more dynamic, replacing office facades after 20/30 years from their construction. E and D also say that in the Netherlands facade glazing is replaced within 20 or 30 years. This seems then a reliable data for the expected lifespan of static glazing. However, as it was made evident by C, not all the facade facade or window component have the same expected service life. Talking about shading devices, F points out how their duration is designed and tested based on use cycles, usually 10.000; therefore, indoor shading's malfunctioning and failure can be often attributed to mechanical overuse. Indeed, F claims that indoor shadings' service life can reach 60 years, in case they are well maintained. F also mentions two issues that can occur when facade elements include electronic components: besides the additional risk of failure due to the increased complexity of the facade systems, electronics components are subjected to updates; the plurality of electronic components in a building can create issues related to compatibility and to its management. This category of issue in absent in buildings that do not involve these components.
Concerning PSW failure mechanisms, instead, E reported that they vary depending on how the AR material is integrated. The AR coating is protected inside the cavity and can be expected to last as much as the glazing, except in case of leakage in the cavity; this could indeed lead to damages related to humidity variation. The AR interlayer is protected as well, so it could be assumed to last as long as the IGU, except in case of delamination. The adhesive AR film instead is more exposed: it can not be applied to face 2 or 3 of the DGU, since it would create problems in the sealing of the glass panes to the spacer, therefore, it is applied on face 4; this means that the Ar film is applied on the indoor face of the glazing, so more protected than face 1 but still exposed to damages, mainly from humidity or scratches. E estimated this solution to last a maximum of 10 years, but specifying that their warranty for these products is 5 years (or only 2 if applied on face 1, outdoor). The warranty for PSW with AR as interlayer is instead of 10 years, but those products have been used in projects for 15 years with no failure registered yet, still according to E.

End-of-Life of AR layers

As B affirms, the End-of-Life of a PSW depends on how its build-up: it is not possible, by now, to separate the coating from the surface of the glass; D mentions that methods to separate coating via laser ablation do exist and are used for enamelled glass, but they produce fumes and would be hard to be applied in the glass recycling process. If cullet used for producing new glass is coated with AR oxides, it shouldn't given issues to the new batch, as suggested by A and D. However, D points out how substances like VO_2 could produce damages to the glass furnace, for example by clogging air pipes or corroding the reflective surfaces, or being dispersed in the air, if proper filters are not applied. Finally, the adhesive layer can be easily separated from the glazing, which can be recycled as usual; according to B, the impact of the film could be estimated as the sum of impacts of the PET and VO2

Table 3.1: Service Life of PSW options according to E

Option	I	II	III
Integration	coating (face 2)	interlayer	adhesive film (face 4)
Expected duration	as IGU (unless leakage)	as IGU (unless delamination)	max 10 years
Commercial warranty	10 years	10 years	5 years

powder. Something similar could be said for the AR interlayer: when the AR glazing is crushed in the recycling process, the interlayer can be separated from the rest. B asserts that it is not possible yet to recycle the AR layer itself, even when separated from the rest of the glass.
The compatibility of PSW with the glass recycling process would nevertheless depend on the AR material used: for example, A stated that liquid crystals are not allowed in furnaces and that a severe legislation defines it treatment process. This shows how the EoL of AR materials can significantly change depending on the category of materials involved and need to be addressed specifically in each case.

3.2.3. LCA

Most of information about the LCA for facades were gathered from C and G: C as a facade contractor that also works on the EPD of their products and G as a sustainability consultancy. However, on several questions C and G answered differently due to the distinct aim of their LCAs: G usually covers the whole life cycle of the products, while C, as a contractor, focuses on the stages under their control, so mostly the assembly and the construction of the facade; the other data are more generic, as for the material production, the use stage and the End-of-Life.

Method, normalisation and weighting

Concerning the LCIA method, C has to follow the standard EN15804+A2, since this is required for the redaction of EPDs in the EU. When G instead uses the Product Environmental Footprint, an LCIA method included in the homonymous framework by the European Commission, named PEF Method and described in Annexes 1 and 2 to "Commission Recommendation on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations" . However, G judges this framework very demanding and difficult to follow due to its extensiveness and to the complexity of the data modelling. By contrast, G considers PEF's LCIA method popular in the industry and safe and reliable to be applied, with a satisfying range of EnICs, 16 in total, and normalisation and weighting sets available; moreover, it is based on the European context. Both C and G make use of normalisation as an intermediate step to apply weighting. G uses the set provided integrated in PEF while C uses the Cost Indicator, based on the Dutch set for Environmental Costs.

Transportation

Considering transportation, G asserts that there is no generally valid rule to apply when the locations are not known but suggests referring to the PEF framework for making assumptions about that. However, G points out how, if the transportation is the same in both the compared cases, its relevance is very low on the overall result.

Uncertainty and missing data

Often, detailed data may be missing; sometimes this is also related to the reluctance of the industry to disclose sensible data on their activity, asserts D when referring to glass manufacturers. G doesn't add specific techniques but states how it is important to rely on information from the material or product manufacturers, when available, and to make assumptions based on proxies when primary data are not available. For new materials, G suggests to model them based on similar ones. However, they point out that it is common practise to focus on the most impactful processes; this can be done by drawing and calculating a first scenario and identifying the most relevant processes in it. Then, iteratively, change and improve those processes that resulted to be more meaningful for the product system considered. Finally, D stresses the importance of description of the data gaps and how these were solved. This is indeed paramount to ensure the transparency of the LCA, especially when uncertainty could be relevant. G also mentions how, theoretically, the uncertainty of data should be taken into account as much as possible; however, G states that, in practise, the calculation of uncertainty focuses on the most contributing processes. Usually, a baseline scenario is drawn and calculated, in order to spot the processes or stages that have the highest impact and, from these, the parameters for the sensitivity analysis are derived; other parameters can be defined before this calculation, in the definition of the products system and of its data, such as the lifespan to consider and the data-set origin.

Operational energy and lifespan

The issue of integrating operational energy in LCA's was confirmed to be one of the most difficult part of the research. G confirmed how considering the building type in this type of analysis can be quite complicated, depending on the purpose of the LCA. According to G indeed, it is hard to attribute the impact of a room to the window, because of the several new parameters needed for the definition of energy simulation. For this thesis's subject, G advice was to show the results of the LCA both including all the stages and excluding the Operational Energy B6: this representation should make more clear the contribution of other stages and processes.
Of course, the impact of the Operational energy depends significantly on the lifespan considered and on potential replacement of the product (or of part of it). C explained how each component of the facade element, especially for facade modules, has a different expected lifespan. In their LCA practice for EPDs, the lifespan of the facade is assumed to coincide with the expected service life of the most lasting component of the facade, generally of 60 years. Each component i is then assigned with a replacement rate r_i, calculated as:

$$r_i = \frac{SL_{max}}{SL_i} - 1$$

For example, in an EPD redacted by C, the glazing is assumed to be replaced 1,4 times (60years/25years - 1). The impact of the replacement module B4 is then calculated as the sum of Production and End-of-Life stages for each component i multiplied by the respective replacement rate.

$$impact(B4) = \sum r_i \times impact(A1_i \rightarrow A5_i + C1_i \rightarrow C4_i + D_i)$$

However, C, the contractor, admits that this is an unrealistic scenario for estimation of the impact; this calculation assumes that each component is singularly replaced after its own estimated lifespan, so that, for example, the glazing and the gaskets are replaced while leaving the frame intact and placed in the building. In practice this doesn't happen and the whole facade module is usually replaced (if not the whole facade). C justifies their choice in the calculation method asserting that, as contractors, they are not able to define the scenario for replacement by themselves; an estimation of this scenario could be done with a better integration of the design process, involving both contractors, designers and consultants. G instead, as a consultant, uses a more realistic and conservative assumption: the building element is fully replaced when the first of its components fails. Basically, they assume for all components the shortest replacement rate among those calculated. exceptions are made if the project includes specific management agreements with the facade manufacturer, such as facade leasing.

Modelling the End-of-Life

The End-of-Life of products is often uncertain. To evaluate its impact, G confirms the importance of drawing multiple scenarios and suggests to start by calculating the most conservative one, defining it as baseline scenario. The other scenarios can be calculated and compared to it, to see how the results do differ.
Moreover, G affirms that multiple waste treatment options can be combined for single components: each portion of waste material, assigned with a specific mass rate, can be assumed to undergo a specific treatment and can therefore be assigned with the corresponding impact. The overall impact of the component can be calculated as the sum of the impacts of the different waste flows.
C asserts that they take their data on EoL from the Dutch National Milieudatabase, which also includes methods and assumptions for EoL. In their EPDs, they include the benefits from incineration, reuse or recycling of the wastes, but these are accounted for based on assumptions: as facade contractor, C claims not to ba able to take responsibility for what happens to the facade at its End-of-Life. In C's opinion, this last stage of the LCA can be quite confusing and vague, if insufficient data are provided, and it could even be excluded from the LCA.

4

Life Cycle Assessment framework

This chapter describes the steps to take in the redaction of an LCA for comparison of Passive Smart Windows (PSW) with another Dynamic Window System (DWS). A general description of the Life cycle modules of PSWs, considering different build-up options, provides a guideline for the Life cycle inventory of the specific products the method to be applied to. Then, indications on the Impact Assessment and its Interpretation are given.
The framework is oriented towards the redaction of comparative assessments of two window products, disregarding as far as possible the specific context of application. However, the indications can be adapted, with the appropriate modifications, to specific projects by using more specific data and assumptions. To facilitate this adaptation, the assumptions and motivations made are always clarified, if possible providing alternatives.

4.1. Goal and Scope

4.1.1. Goal

The goal of this LCA is to make a comparison between a Passive Smart Window and a Dynamic Window System, consisting of a standard window with a dynamic shading device, to determine the most relevant factors in their impacts. In order to assess their overall environmental impact, the two systems are compared across various categories and, if possible, a single End Score. The LCA would be addressed to developers of new technologies, who want to identify the most impactful aspects of their technology in comparison with the DWS but can be extended to designers, who could use it to compare different alternatives or fully consider the different impacts of passive smart windows in their projects.

4.1.2. Scope

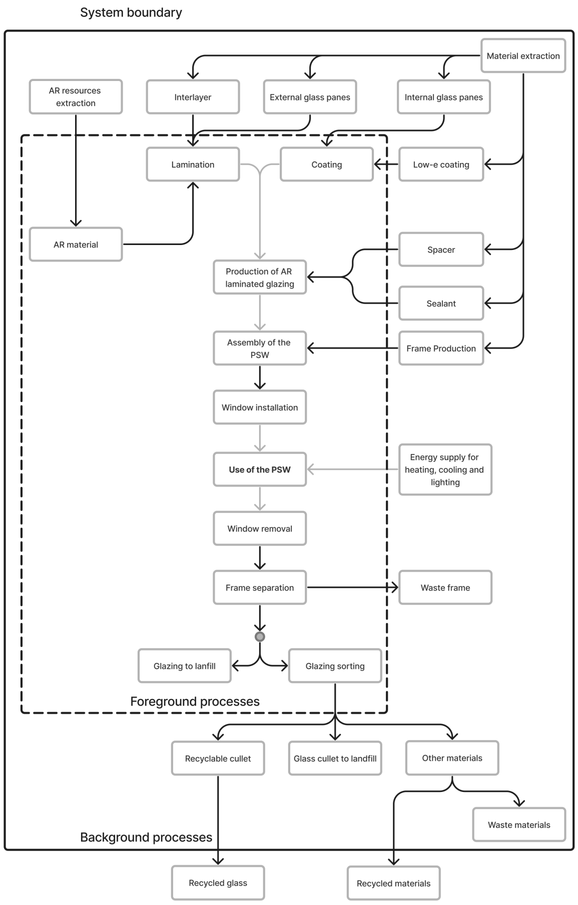
Functional Unit: If the study is considering a PSW as a product, it is necessary to choose the functional unit at the scale of a single building element rather than a whole building. The object of the study is part of the facade system, and must therefore ensure the respective performances, such as thermal insulation, water-tightness, resistance to wind, air permeability, and acoustic insulation while allowing visual light. In addition, it must provide dynamic control of the solar gains without requiring energy consumption for its activation. This considers an area of A_{vis}, defined according to the optimal dimensions the calculation of the energy demand related to an office (from chapter 4.3) and a lifespan of 30 years, based on the average expected service life of glazing.
So the functional unit is a single window of an office facade while providing standard building envelope performances, allowing daylight and controlling solar gains without active consumption of energy for the lifespan of the whole facade system. The reference flow will be therefore referred to the production of that quantity of glazing. The functional unit and the reference flow must be the same for both PSW

and DWS. The main difference between these two products consists of the dynamic component that characterises them, thus the AR layer of the PSW, integrated into the glazing, and the dynamic shading of the DWS.

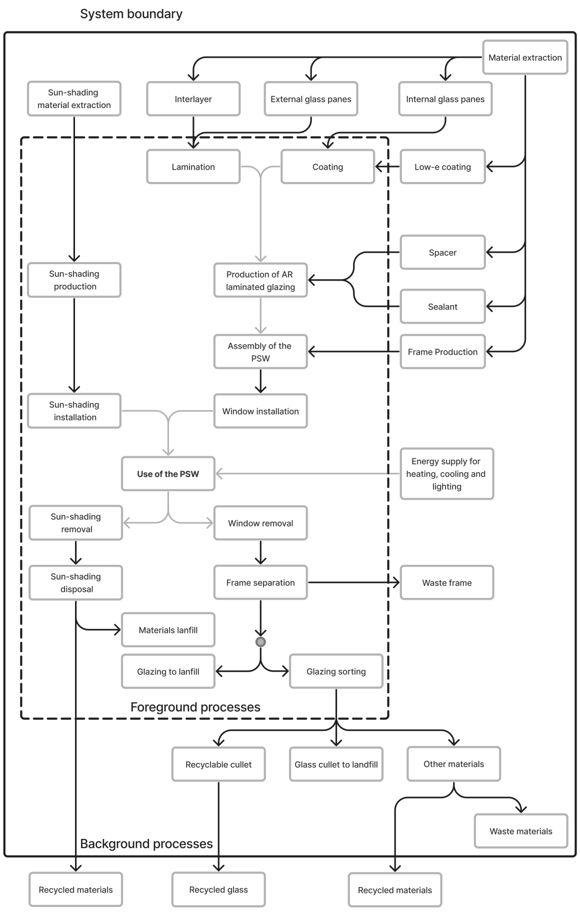
System Boundary: The product system must include all the relevant processes and materials that affect the life cycle of the product but must introduce the assumptions that are needed to narrow down otherwise excessive amounts of data that would be needed.
The analysis should consider all the life cycle stages in a cradle-to-grave perspective, thus from materials supply to the disposal and waste treatment of the used product: this would include the processing of the components, the transport, the use of the product, including operational energy, and the different scenario of End-of-Life. Module D, grouping the benefits that can derive from the reuse, recycling or recovery of waste, has been excluded from the analysis since it concerns the circularity choices that are characterised by very high uncertainty, especially when considering a product not applied to a specific project.
Concerning the PSW, three options of glazing build-up have so far been hypothesised: AR coating (I), AR interlayer (II) and adhesive AR film (III); these three options determine variations both in the production and in the EoL stages, thus three different product systems have been developed, reflecting each of the options. When making the LCA of a specific product, only one of the options must be considered. Since the focus of this framework is on the dynamic properties, the foreground processes should be defined as those that characterise the PSW and the DWS in comparison to StW; this entails all the processes related to the AR layer, thus its production, its integration in the windows, the window use, the End-of-Life of the AR layer and of the components affected by it, and similarly for the shading device of DWS. The other flows constitute the background processes and will be considered mostly with less specific data, thus mostly market activities; this is the case for components such as the frame, sealant, spacer and consumed energy, but also for the production of glass panes, PVB film and low-e coating. For the DWS, most of the activities are related to the production of a static window, thus coinciding with the background activities of the PSW. The foreground processes would be instead those related to the production, use and End-of-Life of the dynamic shading device. Even though in comparisons it is allowed to neglect those processes that are identical in both product systems, for this comparison it is necessary to first verify the ESL (estimated service life) of the components. The ESL of the AR layer affects the ESL of the PSW; therefore, the PSW may be fully replaced during the LCA lifespan, thus requiring the common processes to be repeated, while the DWS can require the replacement only of the sun-shading devices, whose related processes belong only to the DWS product system.

LCIA Method: The literature clearly states how the use of a method with a wide range of categories is needed in order to properly assess the expected environmental impact that the technologies can have. It also expressed how LCIA methods and corresponding normalisation and weighting sets can be related to the geographical context of the study. Both European and Global methods could be chosen for this study; the desire to provide a single end score beside the impact scores for each category implies the choice of a method provided with a suitable normalisation set and weighting set. It is advisable to use widely accepted and recognised LCIA methods: those indeed may be more reliable from the scientific perspective, thus making use of a robust characterisation model, on the target perspective, since the categories expressing the result may be more recognisable and easier to be understood, and on the practical perspective, being more easily compatible with database and software.
The use of normalisation and weighting may be useful for identifying the product system or the scenario with the highest overall impact, thus it is advised to choose an LCIA method provided or compatible with reliable normalisation and weighting sets. In this regard Environmental Footprint 3.1 and ReCiPe2016 can be suitable choices, the first one provided with its own sets and the second one compatible with the Environmental Prices weighting set.

Software and data sources: The software can imply some differences and give some limitations: not all software implements all the possible methods. Free software are as valid as those that require a subscription, even though the last ones may have additional features, that help in adapting the data, for example, if they are missing for specific locations or if they need to made more generic, or in analysing them. However, software can have very high costs, so usually the practitioners use those that are



(a) System boundary of PSW, including processes related to the AR layer



(b) System boundary of DWS, including processes related to the sun-shading device

Figure 4.1: System boundary for the two product systems. The black arrows identify transports.

already available to them. Therefore, it is acceptable to choose a software that is already available to the user, either because it is free or because it is already available in the institution or company the user works for. If it is desired to make an investment for a subscription, it is important to first determine in advance what it will be used for, in order to check the available methods, the data compatibility, the aim of the software and the additional features it can provide.
For the database, a similar discussion can be made: first of all, it is meaningful to check what databases are already available to the user and if the data within it are conforming to the chosen system model. For the evaluation of PSW, both data about the construction sector and data about chemical processes may be necessary. Moreover, since the PSW is being evaluated as a product, it is advisable to use the Allocation cut-off system model.
The choice of the software and database could also determine the choice of the LCIA method due to compatibility reasons: the database must indeed provide, for each process, the elementary flows used by the characterisation model of the method and the method must be integrated in the software too. Corresponding normalisation and weighting sets are instead easier to implement in the software.
Since Auto-Responsive materials are still under development and their integration in PSW not very diffused yet, it is very hard to find suitable data about them on databases; EPDs are also quite rare, if not impossible to be found, so the some processes related to this material need to be modelled by the LCA practitioner. To do so, it is important to rely on experts: the market can provide an understanding of the processes involved in the production, specifically on the modality of integration of the AR layer in the glazing build-up, including the procedures involved in this phase, with the respective energy demand, resources used and wastes produced. When possible, it is advisable to base the newly modelled process on similar ones already in the databases. The modelling of the End-of-Life processes can be the most complicated one due both to the scenarios' uncertainty and to their unknown impact. An example could be the impact of VO_2 coated cullet in glass furnace: this is assumed to evaporate when the cullet is melted, but the possible effects of VO_2 vapour in the furnace itself or end in the atmosphere are mostly unknown, and the same could be for other materials used for Photochromics or Thermochromics.

4.2. Life Cycle Inventory

4.2.1. Assumptions

Foreground processes

Since the focus of this assessment is the comparison of the effect of the dynamic effect of the PSW and the DWS, the foreground processes are those that involve directly the components of the window that determine this dynamic behaviour. Therefore, the foreground processes will concern mainly the AR material and the components it is integrated into, for the PSW, and the blinds, for the DWS. Special attention should be paid to the processes that differ between the two product systems, both in defining them and in modelling them. The components and processes that are common to the two product systems should be regarded are background, for example, the production of the glass panes, or the production, supply and E-o-L of spacers, sealants and frame; the same can be said for the processes such as installation and de-construction.

The glazing build-up

The glazing build-up should be as similar as possible between the PSW and the DWS. Unless of comparisons between specific products or product categories, it is advisable to use the same build-up in the glazing, except for the AR layer. If no specific data are available about the tested build-up, a generic one should be used. In that case, it is suggested to use double glazing unit, with an outer laminated glass pane and low-e coating on face 5 (figure 4.2). According to the interviews, indeed, the majority of the windows currently manufactured for new buildings in the western market are double glazing units, with some exceptions for Germany and Austria and for high-rise building in the UK, where triple-glazing units are often being used. The laminated glass pane and low-e coating on face 5 are commonly used in order to grant suitable safety and performances, both thermally and acoustically. For performance-related reasons, the cavity of the DGU is often filled with specific gas mixes.

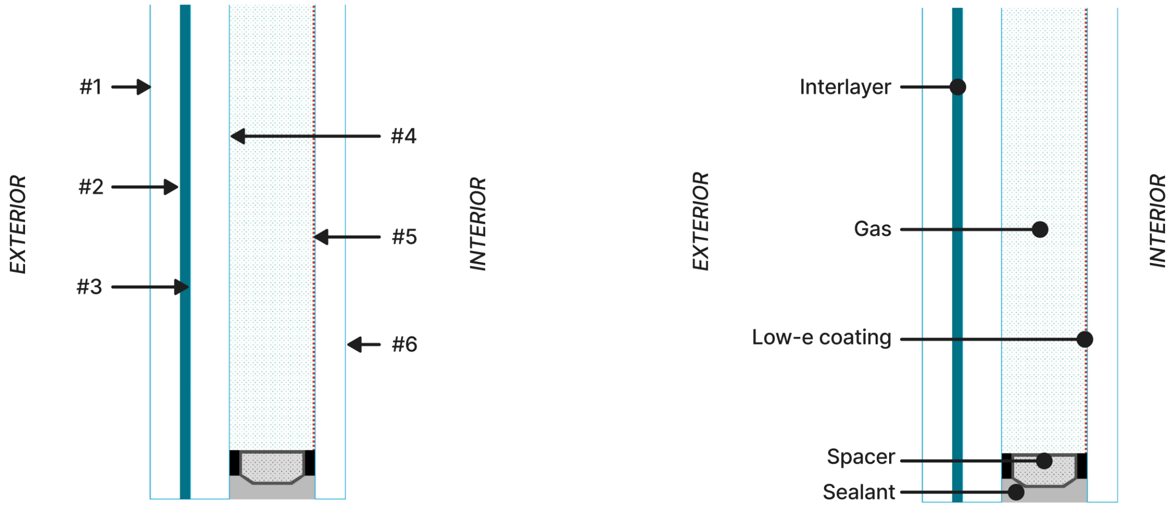


Figure 4.2: Schematic section of a DGU with laminated glass, showing the surfaces number (on the left) and some components (on the right).

Concerning the PSW, the outcome of the interviews showed that there are three options to integrate the AR layer in the build-up: as coating on face 4, as lamination interlayer between faces 2 and 3 or as adhesive film on face 6.

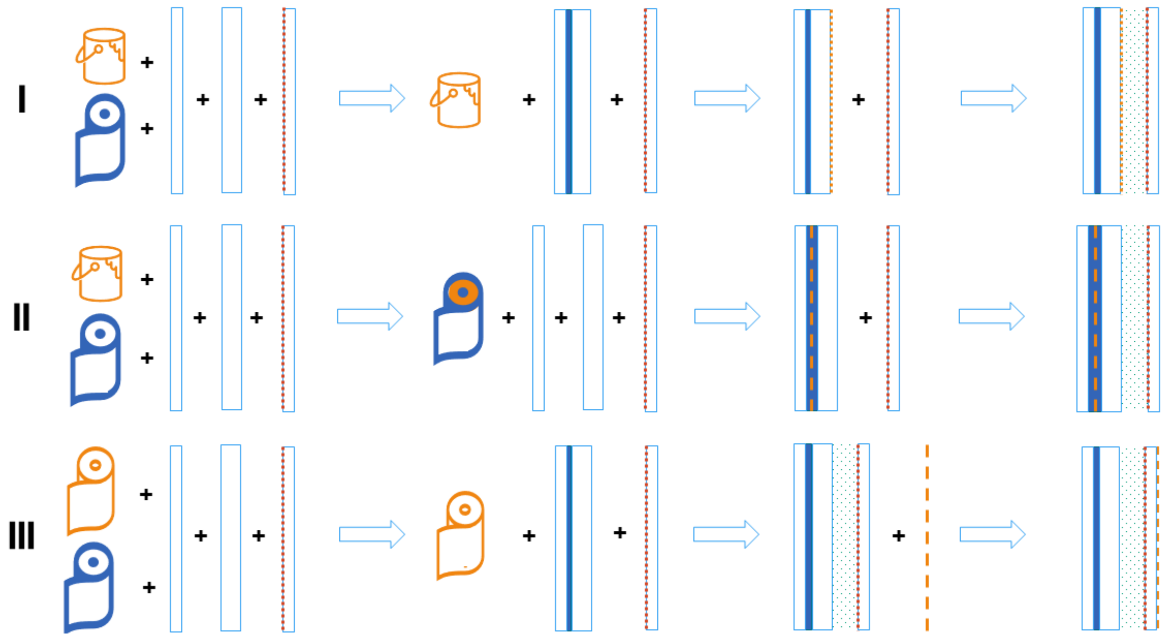


Figure 4.3: Schematic process of the 3 options for PSW production

These options are illustrated in figure 4.3 and here described:

I AR coating: the responsive layer is applied as a coating to one pane of the laminated layer, usually through spin-coating or dip-coating. These processes cannot be integrated into the production chain of flat glass glass, thus implying a higher cost of production. The AR coating has not been widely developed yet, but it is mostly used with Thermochromics and is usually applied to the laminated pane, on face 4: being positioned in the cavity of the glazing, the coating is protected from mechanical damages, such as scratches, and humidity variations that could affect its efficacy

or durability. Since the mechanical properties of the responsive layer cannot be assumed in advance, the coating could be damaged by the high pressure and temperature used during the lamination process; following a conservative approach, it is suggested to assume that the coating is applied after the lamination.
There is a lack of knowledge about the durability of this coating but, according to PSW suppliers, that could be affected by leakage in the cavity, which would imply loss of performance in static glazing as well.

II AR Interlayer: the AR material layer is applied as an interlayer between the two laminated panes. This implies that the integration of the AR material doesn't require any additional passage to the glazing production. However, the different manufacturing of the interlayer material would need to be taken into account. Indeed, the interviews suggest that the AR material can be added with different techniques: it could either be embedded in the polymeric interlayer, usually PVB, or could be applied on a PET film. In both cases, additional layers between the glass panes might be necessary, either for stabilizing the material or for ensuring adherence between the panes. It is therefore important to investigate, as far as possible, the composition of the interlayer. This technique has been used industrially for Thermochromics but not for very long: products applied in projects realised around 20 years ago are still functioning, according to a supplier. They claim that the expected service life of an AR interlayer can be assumed to be the same as a regular laminated pane, but no certain data are available yet in this regard.

III Adhesive layer: the responsive layer consists of an adhesive film, which is applied to face 6 of the glazing, and is mostly used for Photochromics. This makes this option suitable especially for renovations, where it is attached to existing glazing, but more vulnerable as well. According to a supplier, the expected lifespan should be around 10 years. However, this option would allow the replacement of the only AR layer in case of failure, a solution that is not possible in other options .

The differences between the three PSW options determine differences in the life cycle of the PSW as well, especially in the Production and End-of-Life stages. However, they are assumed not to have influence neither on the Construction Stage nor on the Use Stage, except for the Replacement module B4.

Locations and transport

The life cycle of PSW and DWS requires to consider several locations, especially for the manufacturing, assembly and E-o-L of the products and of their components. If the specific information about the two analysed products are unknown, it is important to consider that these elements can undergo several and different movements. The difference between systems can lay either in the quantity of transported material, in the route distance or in the mean used. For example, glass panes can be produced and manufactured in one location, assembled as glazing unit in another one and the frame may be assembled in a third place. Following, the main locations to be considered are reported, describing the activities that could generally be assumed to host:

- *Raw material Origin site (RO)*: AR compounds used in PSW rarely derive from recycled materials, so it is useful to consider the extraction of the raw material needed to produce them; this location may host also initial transformation process of the raw material. If this location is unknown, it is legitimate to choose it based on the most frequent origin of the used raw materials. In case multiple possible locations are found and their distance form the next location vary significantly, it may be necessary to test different scenarios for this.
- *Compound Production site (CP)*: the AR compound are produced through chemical processes, more specific than those used for the initial transformation of the raw materials. If this location is unknown, tit could be identified with the producing company. From here, the AR material is assumed to come out either as layer (on a PVB or PET substrate) or as powder for coating. In the option I, the laminated pane may be delivered to these location and coated with the AR material.
- *Glass Production site (GP)*: in this location, the glass panes are produced, coated and laminated. It is advisable to keep this location common between PSW and DWS product systems. *If a specific location is not known, it s advisable to consider one of the production site of the glass supplier or,*

if this information is available, to choose one either in the same region as the CP or in the region closer to the building site. For option II, the AR material as interlayer is here added to the glazing.

- *Glass Assembly site (GA)*: if the IGU manufacturer does not coincide with the panes manufacturer, it may be necessary to consider an additional location for the manufacturing of the IGU. Here the spacers are bents and sealed to the glass panes, finally filling the cavity with the gas mix.
- *Window Assembly site (WA)*: In this location the frame is added to the glazing. This location will be the same for any option of PSW and for DWS. In the option III, here is where the film is attached to the window surface.
- *Blind Production site (BP)*: this is the location where the shading devices is produced, ready to be applied to the window. The production of sun shading devices, blinds especially, is quite well establish in the industry and it can their productions site is not subjected to specific geographical restrictions (as it can be for GP do to the plant size). Therefore, unless for more specific indications, this locations can be assumed to be in the same regions a the building site.
- *Building site (B)*: location where the building is constructed

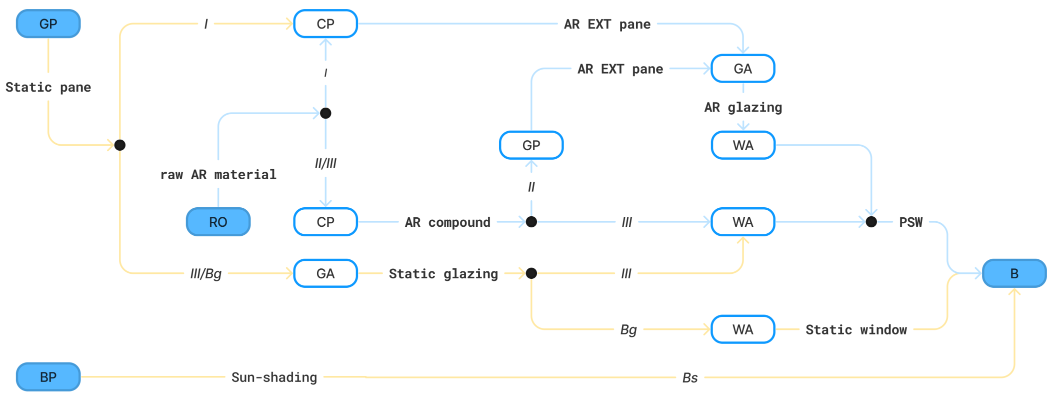


Figure 4.4: Scheme of the window production, considering all options and DWS. The rectangles identify the different locations, each arrow indicates a transport and is assigned with one or more of the option (I: Ar coating, II: AR interlayer, III: AR adhesive, Bg: StW glazing, Bs: sun-shading). The blue arrow identify transports that involve the AR components, wile the yellow ones the others. The locations in blue represent the start (GP, RO and BP) and the end locations (B).

This diagram becomes simpler as one of the PSW options is chosen and the transports related to the others are eliminated. Moreover, this diagram could be further simplified by the unifying some of the locations, according to the knowledge available on the compared products and on the relevance of the correlated transports in the comparison. For example, if the PSW and DWS have different build-ups or are known to be manufactured in different locations, it may be important to keep the passages and locations distinguished. Before considering the scenarios, several locations need to be defined.
As for the Production stage, for the End-of-life several locations may be needed as well, both for the waste treatment and for their final disposal. The following locations are determined by the most likely scenarios, chosen according to the results of literature review and interviews. All this locations should be chosen in the same area or region of the building site. Of course, there could be exceptions. if more precise data are available; this could be the case for innovative solutions for facade management, such as facade leasing, or for the known chain management of specific wastes.
Concerning recycling, facilities for the reuse of recyclable material are illustrated as well.

- *Waste Processing site (WP)*: this is the location where all the operations related to the treatment of the glazing are carried out: the adhesive film, if present, is removed, the glazing is crushed and sorted.
- *Glass Production site (GP')*: here, part of the cullet is remelted to produce new float glass. This process is part of a new product system, so it is not considered in this LCA. How to account for

the fraction of material flow depends on the chosen system model. Usually, this location shall be different from the GP where the glass is produced: the new location will likely be in the same region as B and WP. Exception can be made if the glazing manufacturer implements specific waste management policies, that may entail the recover of their glazing at the EoL.

- *Glass Recycling site (GR)*: in this location the glass cullet coming from the glazing processing are recycled to make products of lower quality, such as glass fibers or glass containers. Therefore, this doesn't represent a real location but gathers a group of possible different locations that would provide this function, depending on the possible end of the product. Again, this may belong to a different product system and should be considered coherently with the chosen system model.
- *Blind Recycle site (BR)*: in this location where the blinds are recycled, according to their material. In case of recycle scenarios, they are transported here right after being removed from the building. Not all components of the blind may be recyclable so they should be distinguished.
- *Heat Recover facility (HR)*: in this location, all the wastes that need to be burnt are gathered. The energy needed to burn the wastes is accounted for as an input while the recovered energy is as a beneficial output, to account for depending on the system model.
- *Landfill site (L)*: this site is assumed one for all the products sent to landfill, disregarding the previous treatment that they may receive.

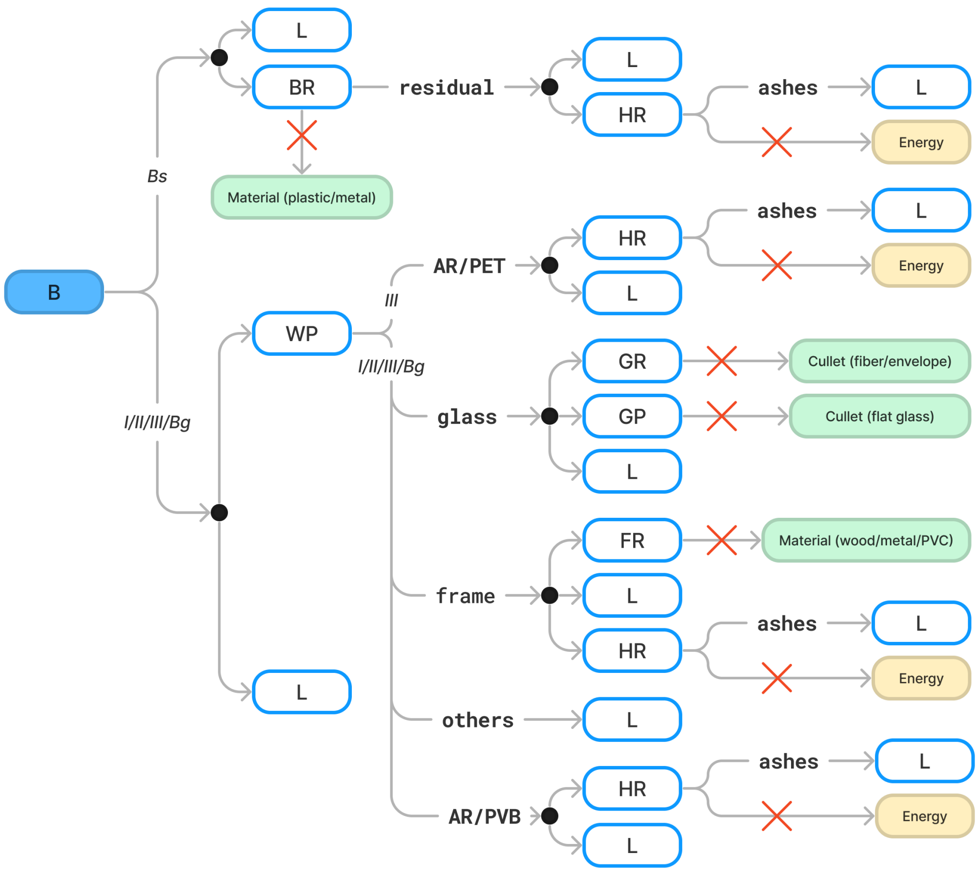


Figure 4.5: Scheme of End-of-Life scenarios. The rectangles identify the different locations, each arrow indicates a transport and is assigned with the transported product (in bold) and one or more of the options (I: AR coating, II: AR interlayer, III: AR adhesive, Bg: static glazing, Bs: sun-shading; in italics). The green and yellow labels identify beneficial outputs that could be considered in the D module, but neglected in the cut-off system model

Lifespan and expected service life

An important aspect to define is the lifespan of teh LCA: on one hand, a lifespan must be defined for the whole life cycle, mainly referring to the facade itself. On the other hand, each element has its

Expected Service Life (ESL) which is usually shorter than the overall lifespan. When a building element fails, losing part of its performance, it must be replaced to ensure the proper functioning of the facade. This implies the early disposal of the original product and the additional production of one or more new products, basically replicating the impact related to these stages for that product. This can be a very relevant factor, especially if the compared systems are replaced with different frequencies.
The impact due to the replacement of a component can be expressed through a replacement rate; this can be estimated as the ratio between the life cycle lifespan and the component's ESL, rounded up and subtracted by 1:

$$r_{comp} = \left\lceil \frac{LS}{ESL_{comp}} \right\rceil - 1$$

This approach is the most conservative but the most realistic: building components are object and as such that their replacement must be expressed by a natural number. In addition, the different components of the same product may have different may have different ESL: being the window a whole object, it is unrealistic to consider each component to be replaced at its own rate but the whole product would be fully replaced when the first component fails. The replacement of a single one would require at least removing and disassembling partially the window and this practice, which is still far from being common in the building sector, would somehow implicate the manufacturing of a new product through reuse, which is out of the scope of this LCA. To conclude, the ESL of a window can be identified as the shortest of the ESLs of its components, thus:

$$ESL_{window} = min\big(ESL_{comp,i}\big)$$

and

$$r_{window} = \left\lceil \frac{LS}{ESL_{window}} \right\rceil - 1$$

4.2.2. Life Cycle Inventory model

In this section, the stages and modules of the life cycle are analysed, concerning both the Passive Smart Window, with different possible options, and the DWS. The different glazing build-up options require to make distinctions both in the Production stage, in the Manufacturing module A3, and in the End-of-Life Stage, when considering the waste treatment and disposal C3 and C4.
It is important to stress the distinction between the DWS' static window and the shading device. While the window has a very similar life cycle to the PSW, the sun-shading device basically has a separate and parallel life cycle. Nevertheless, it represents the dynamic component of DWS and, together with the AR material, it is the main difference between the two product systems. The diagram 4.6 illustrates all together the three options of PSW and the DWS: the processes and products in grey are common to all the PSW and DWS, since they belong to the life cycle of the static glazing. The colours represent instead the changes introduced by the use of a dynamic component. DWS is presented in orange and its section concerns mainly the sun-shading device. Option I, the AR coating is represented in blue, option II, the AR interlayer is represented in purple and option III, the AR adhesive layer, is represented in green. The reference flow, thus the PSW or the StW, is highlighted in red.

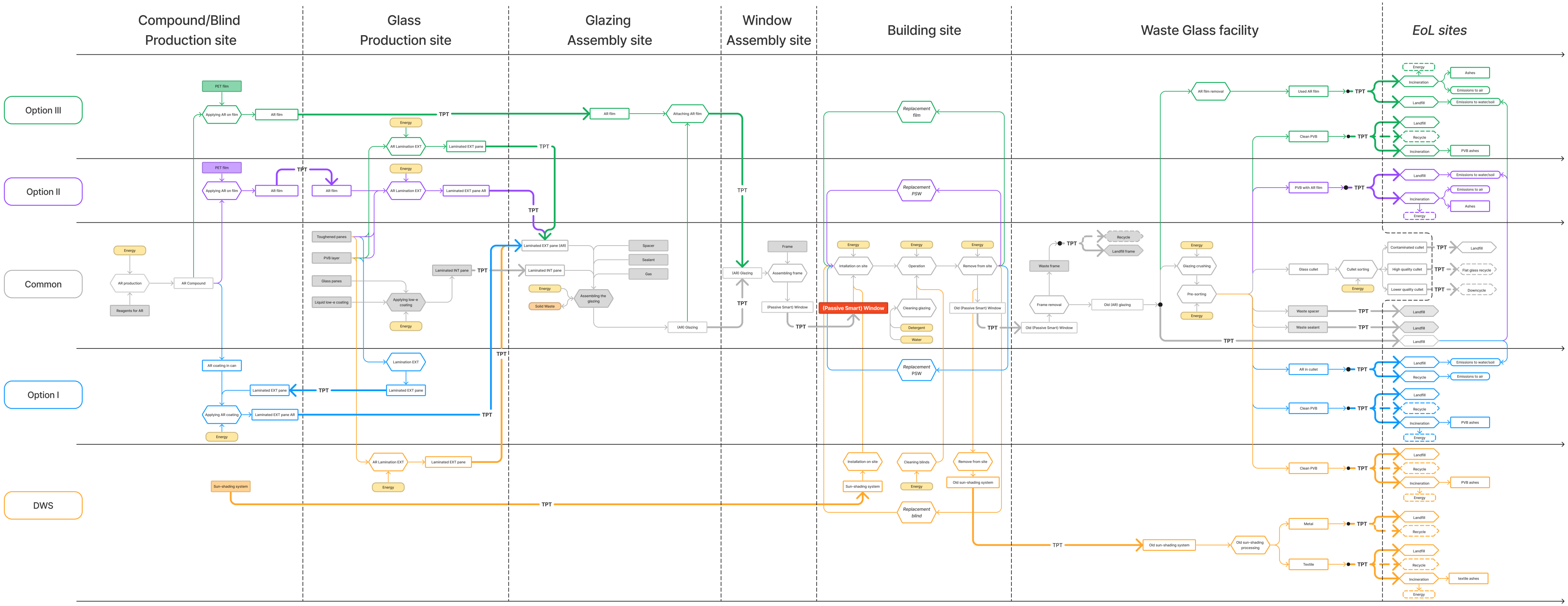


Figure 4.6: Diagram of the product system with the four options: three for the PSW options and DWS. The parts in grey are common to all the options, the coloured ones correspond to a specific option. Rectangles indicate the products while the hexagons represent activities. The vertical dotted lines group different activities, based on the generic location they would take place in, which are noted at the top of the diagram. The activities are connected by arrows; thick arrows with the text "TPT" indicate transport from one location to another, whose impact would need to be accounted for.

Production Stage

This stage describes the production of DWS and PSW, ready to be transported and installed on site. For PSW, this stage may vary more or less significantly depending on the option chosen and on the specificity of the AR material used. The shading device of DWS can be considered through EPD provided by the supplier or via a generic EPD. These usually include already the impact of this whole stage, which can the be considered with one single process.

A1 - Material Supply: This module includes the supply of the several component at different stages of their manufacturing, depending on the specific case. The involved products in general, except for the foreground ones, should be assumed to be identical to the three PSW options and to the DWS: these can be the glass panes, frame, sealant and spacers, as well as for low-e coating application and lamination processes. Data for market activities can be used as well.
The extraction of the raw materials for AR material and the production AR compound belong to this module.

Option I, option II and option III: the raw material needed for the production of the AR compound is extracted and processed. It is advisable to use data and information from the supplier about the fabrication of this material and, when those are not sufficient, to complete the with studies evaluating the considered substance. The compound usually consists of a powder, to be embedded in a polymeric layers (option II and III) or in a liquid coating, to be applied directly on the glass surface. If additional material is needed, such as a PET layer of additional PVB compared to a standard DGU, that should be accounted for.

A2 - Transport: The transport in this stage considers the movement of all the components between the various sites. This stage is simpler but less precise when considering market activities for the supply of background materials, such as glazing and frame. If few information are known about the specific production chain of the windows, some locations can be agglomerated in one, simplifying the calculation for transport. These shall not be done if the routes are know, especially if they differ between the PSW and DWS.

A3 - Manufacturing: In this module the assembly of the window is analysed. The assembly is basically identical for all the options and the DWS. It includes the assembly of the glazing unit, assumed to be a DGU and the assembly of the frame on the glazing unit, giving the window as final product. Only option III requires an additional process. Lamination and coating application must be accounted for, if the supplied background products do not include these passages yet.
For option I, the laminated glass is coated, usually through either dip-coating or spin-coating. For option II, the embedding of the AR material in the PVB and eventual variation in the impact of the lamination process should be accounted for. The embedding of the AR material in the PET film should be evaluated for option III. After the DGU has been assembled, the adhesive layer is applied on the face 6 of the glazing. Then the assembly continues as in the other cases. Unless any machine is specifically required for this, the film can be assumed to be applied manually.

Construction Stage

In the Construction Stage, no parallel options are analysed. Given the assumptions previously made, the different types of options for the PSW would not have any influence on the Construction Stage. An exception could be made about the thickness or weight of the windows. A deeper analysis of the build-ups' thicknesses would provide more precise information.

A4 -Transport: Building site location and means of transport would play an important role in this stage. The already assembled windows will be transported to the building site from the assembly site; except in case of relevant weight differences, the PSW and the DWS window will have the same impact, so they can actually be neglected. The only difference to take into account when considering the DWS, is the transport of the shading from the shading production site to the building site.

A5 - Installation: On the building site, the window is installed in the building. Again, this process has the same impact in all the cases; indeed, on of the advantages of the PSW is that they substitute static windows using the same installation procedure and without implying additional work. in addition, the impact of the installation process is often neglected due to its low.
For the DWS, the installation of the shading device is to be considered. This has been assumed to be systems that is attached to the window on site, usually manually.

Use Stage

For this stage, some modules can be considered negligible, namely Use (B1), Repair (B3), Refurbishment (B5) and Operational water (B7).
For this stage, some modules can be neglected. Use (B1) and Operational water use (B7) do not apply to this case: PSW and DWS (if no automatic activation is considered) are both passive systems and their functioning does not require any consumption of water. Repair (B3) does not apply either: any damage occurring to other components than the glazing would have the same chance to happen in both product systems, so it can be neglected; at the same time, damages to the glazing would imply its full replacement and the same could be said for the shading device. Finally, the Refurbishment (B5) was neglected as well, due to its similarity with Replacement (B4).
A particular attention is given to the module Operational energy (B6), which is expected to play a relevant role in the overall comparison will rely on the results of building energy simulation.

B1 - Use (excluded) Both PSW and DWS doesn't imply any emission during their utilization in the facade, at least no emissions connected to the responsive layer or the shading device.

B2 - Maintenance As aforementioned, PSWs are very similar to static windows in terms of build-up since the responsive layer is inside the glazing unit. The responsive layer is not expected to be acted on during the lifetime of the PSW so it doesn't require any additional maintenance, compared to the static glazing. The maintenance of the glazing would normally consist only in its cleaning. A reference for cleaning of glazing can be found in EPDs, where it is estimated mainly as the consumption of water and detergent for a certain frequency, accounted for the whole lifespan of the facade. However, this module a low impact in the overall assessment and is being identical in the two product systems, so it may be neglected .
The sun-shading device may need regular cleaning; in most of EDPs this is neglected or accounted for that yearly, so still with a very low impact.

B3 - Repair (excluded) The Repair module for the glazing is excluded since the replacement of single parts of the window has been considered not realistic. The difference in the window between the compared cases (PSW and DWS) doesn't rely on the frame but exclusively in the glazing unit, so any possible damage to the frame will be neglected.
The only component that could be repaired is the sun-shading device of the DWS, which is exposed to continuous mechanical movement, due to the action of the users and to the solar radiation. These factors can lead to the breaking of the actuating mechanism or to the deterioration of the shading materials (especially with fabric). The mentioned damages could imply the substitution of just some elements of the shading.

B4 - Replacement In this part, no deterioration connected to the glazing in general is considered, but only the phenomena connected to the dynamic components, namely the AR layer and the sun-shading device.
As mentioned, the impact of the replacement consists in the repetition of the impact of Manufacturing, Construction and End-of-Life stages. It is therefore very impactful and must be calculated correctly, depending on the expected service life of the products (ESL) and the lifespan of the facade facade. As a general rule, the impact of the replacement stage, can therefore be calculated as the combination of the mentioned stages:

$$impact(B4_i) = r_i \times impact(A1_i \rightarrow A5_i + C1_i \rightarrow C4_i + D_i)$$

In general, for simplicity, it is advisable to consider the product to be replaced with an identical one, disregarding eventual evolution of the technology itself which would affect the performance and the operational energy use, or of the related infrastructure, which could modify the impact of Production and End-of-Life.
Lifespan range of facades systems can be quite wide, also depending on the context: the interviews pointed out how this can be between 25 and 30 years in North of Europe, while being longer, around 50 years, in Southern Europe. However, the lifespan used in the literature review were longer, between 45 and 60 years, with not significant geographical difference. It may then be advisable to assume, conservatively, a shorter facade lifespan.
The ESL of a window is usually assumed between 20 and 30 years. While this can be a realistic number for the static glazing of the DWS, the PSW must be evaluated more carefully. Indeed that depends on the AR material itself and on how it is integrated in the build-up, thus it should be defined based, as much as possible on the information provided by the product supplier
An important distinction must be made between elements that consists of separately replaceable components, such as option III, and those that can only be replaced as a whole, such as options I and II.

Option I and option II Both the AR coating and the AR interlayer and well integrated and protected in the glazing and, according to suppliers, could be regarded as durable as static windows. damages to the AR coating to to infiltration in the cavity or to the AR interlayer due to delamination may have the same chance to happen in a corresponding static glazing. However, the novelty of this products implies the lack of reliable data on the ESL, since only few projects have been realised for a long time now and no studies were found on the state of their Passive Smart Windows. It is therefore advised to be cautious with the choice of the ESL and to consider uncertainty and to consider that the failure of these layers would imply the failure of the whole window and could be seen as the weak component of the PSW. Consequently, the replacement rate would be:

$$r_{PSW} = \left\lceil \frac{LS}{ESL_{PSW}} \right\rceil - 1$$

Option III The AR adhesive layer is significantly more fragile than the other options, being it exposed to variations of the air conditions of the indoor space and to the risk of scratches. According to a supplier, this option can be expected to last maximum 10 years. However, it is to be noticed that in this case the AR layer can be replaced without affecting the rest of the window, thus reducing the impact of the single replacement, in comparison with the other options. the replacement of the glazing and of the AR layer could then be distinguished by suing two separate rates:

$$r_{PSW,AR} = \left\lceil \frac{LS}{ESL_{AR}} \right\rceil - 1$$

and

$$r_{PSW,window} = \left\lceil \frac{LS}{ESL_{StW}} \right\rceil - 1$$

In this case ESL of the window is considered the same as the ESL of the benchmarking static window

DWS For DWS, a distinction is necessary. Usually, DWS should be treated similarly to to option III, distinguishing two components: the window, properly defined, and the sun-shading device. This can be the case for indoor blinds or external movable louvres. As a consequence, the replacement rates can be distinguished:

$$r_{DWS,window} = \left\lceil \frac{LS}{ESL_{StW}} \right\rceil - 1 \tag{4.1}$$

and

$$r_{DWS,shading} = \left\lceil \frac{LS}{ESL_{sh}} \right\rceil - 1 \tag{4.2}$$

In case of shading devises such as cavity-integrated venetian blinds, the whole DWS should be replaced all at once, thus with the replacement rate:

$$r_{DWS} = \left\lceil \frac{LS}{ESL_{DWS}} \right\rceil - 1 \tag{4.3}$$

B5 - Refurbishment (excluded) The refurbishment of the building was neglected since it was not considered a relevant factor. In case of partial refurbishment, only indoor elements of the building would be involved, thus not affecting the facade system (so not involving the PSW and the window of the DWS). The shading devices, especially if placed inside, could be regarded as part of the furniture and changed according to the customer needs and desires, but this would be accounted for as replacement. A full refurbishment instead would preserves mainly the building structure, changing any other part of it, including the facade system. This would then coincide with the E-o-L of the whole facade.

B6 - Operational Energy Use The operational energy use of the building is the energy consumption in the building due to the use of the considered technology. PSW is a passive system, so it doesn't imply any energy consumption from the building; DWS is a manual system thus avoiding any energy consumption from the building too.
However, both PSW and DWS are window systems aimed to the control of solar gains, so they have an influence on the energy consumption of the building as a whole. The Operational energy use B6 will be calculated by simulating the yearly energy demand through an energy simulation model as defined in 4.3. The yearly energy demand, multiplied for the lifespan of the LCA, will be used as inputs for the processes used in the B6 stage. These can be defined differently depending on the level of detail know for the application and on the assumptions made in terms of building and systems used. In general, electricity mix and heating supply provided by for country or region, which can be used heating and electricity will be then used as inputs values for the processes related to the operational use in the LCA software, according to the procedure established. The corresponding LCI processes can consist of an electricity mix and heat mix consistent with the geographical scope.

B7 - Operational Water (excluded) During the use stage, no water will need to be used for the functioning of PSW and DWS. The water that will be used for the cleaning of the glazing, on the outer and on the inner surfaces, could to be accounted for in B4.

End-of-Life Stage

The End-of-Life of a product starts whenever it is replaced, dismantled or deconstructed. In this study, no repair has been considered so this is applied only at the end of the service life of the product, both for the PSW and the DWS.
This part of the life cycle is the most uncertain for two main reasons. First of all, contrarily to the production and use stages, the End-of-Life of products is always hard to be foreseen precisely: many scenarios are possible but the level of uncertainty of each is very high since the actions related to the dismantling and disposal of products are far in time from the design; as a consequences, technologies and facilities can change, making it hard to plan from the start where and how to dispose of the products, information on the products can get lost, so more advanced and sustainable possibilities of disposing the product may be disregarded, or the need or desire for quick dismantle of a building can result in a less elaborated or sustainable disposal of its components.
Secondly, the current development of the PSW technology offers very little information about its End-of-Life, if not at all. Few samples o PSW have been applied so far and a procedure to treat these product after their service life has not been established yet. Besides for the removal module (C1), the different build-up options determine different end-of-life scenarios which will be therefore considered separately.

C1 - Removal: The removal of the windows from the wall has the same impact in all the cases and can thus be disregarded. For the DWS, the removal of the shading devices is to be considered as additional but, as for A5, EPDs often assume it to be done manually and thus neglect it.

C2 - Transport As for the previous transport modules, this is extremely influenced by the locations as well. For simplicity, all the transports are assumed to be made by lorry. The size, typology and load of the lorry though vary depending of the transported material. The figure 4.5 summarises the End-of-Life stage, where the different components are separated and where they are transported. According to the different load transported, the mean of transport may vary slightly. The scheme take into account all the options (I, II, III) as well as the DWS, separated in static window (StW) and sun-shading .
Most of the locations are assumed to be the same for all the options; on one hand, this assumption has been made for sake of simplicity. On the other hand, it is reasonable to assume that the same type o treatments would be executed in the same location. Therefore, the Waste Processing site, the Glass Production site, the Heat Recovery facility and the Landfill are considered to be the same in all the options and scenarios.

C3 + C4 - Waste Processing and disposal In this module, different scenarios are considered for each options (I, II, III) and for the two main component of the DWS, the DWS and the shading device. The reuse has been excluded from the possible scenarios: the reuse of windows or of float glass is still rare and it is a complex process that depends strongly on the conditions of the component at the End-of-Life of the building and on the design it will be implemented in. The sun-shading device's lifespan, usually shorter than the window's, is too short to allow it to be reused for a significant amount of time.
Little knowledge is available about the E-o-L of the AR material. Since PSWs have only recently been applied established waste treatment process does not exist yet. However, PSW can be assumed to be treated in the same way as static windows, thus considering several different scenarios, even though the impact of these scenarios may change depending on the specific material used for the auto-responsive layer and on how this is integrated in the build-up of the window.
The waste processing concerns mainly the separation and treatment of the various components of the window. The frame can be considered to be removed and treated from both products. Then, the glazing can either be sent to landfill or be treated for recycling, but this may differ depending on the PSW option considered. While landfill seems to be the most common practice, the recover, treatment and recycling of the glazing components depends on the chosen geographical scope, since is possible only in those countries or regions where the flat-glass industry developed and implemented it, such as France of the Netherlands. Following, the different scenarios will be illustrated and the corresponding waste treatment process explained.

Landfill is still one of the main scenarios in case of disposal. In this scenario, which is considered possible for all the options (I, II, III), the whole glazing is sent to landfill as is the sun-shading device . The impact of the glazing each option can be calculated as the addition of the component such as the glass panes, spacers and sealant, the PVB interlayer and, for the PSWs, the AR layer. The impact of this last component is generally unknown since it is too rare to be found in LCA databases; therefore, it can be estimated as the sum of the impacts of the components of the AR compound or through the comparison with similar components that are present in the database. This estimation shall be carried out with a conservative approach; however, this approach is not strongly reliable itself , since chemical compounds don't have the same effect of their own components but can vary in several aspects. As far as it is possible, this estimation should be based on the observations of expert and especially, if available, those of the manufactures of the material itself. Since reuse has been discarded from the scenarios, recycling of the material is the most sustainable possibility for the considered products. Even though the benefits related to recycling will be cut-off, it is relevant to analyse this scenario. As assessed in the interviews, re-

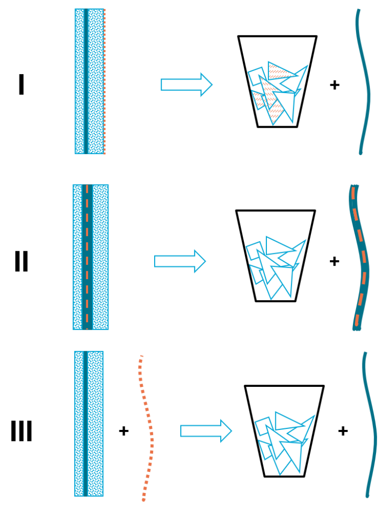


Figure 4.7: Scheme of the separation of the glazing components at the End-of-Life for the three PSW options

cycling of glazing is not very common around the world and
only few countries, mainly France and the Netherlands, have developed as structured recover chain. The recycling shall thus be considered only if it is coherent with the context.
Glazing waste treatment for recycling consists of several passages, all assumed to take place in the Waste Processing Facility. For all the options (I, II, III, StW) the glazing is processed in the same way, thus by crushing it in small shards; the resulting cullet undergoes several sorting stages to remove metallic components, ferrous and non ferrous respectively through magnetic and Eddy current, lightweight impurities, liker rubber residuals, and CPS (ceramic, stone and porcelain). The glass cullet is then sorted per quality, in order to destine it either to flat glass production or to the production chain of lower quality, such as glass enveloped (bottles) or glass fibers. Meanwhile, on-glass parts are separated and redirected to other cycles: sealant and spacer follow their own E-o-L. The PVB E-o-L is either sent to landfill, incinerated or, in some rare cases, recycled.

Option I: the coating cannot be separated from the glazing and will contaminate the batch. From the interviews it was assessed how some materials, such as liquid crystal, may not be accepted at all, and redirecting the whole glass to be redirected to landfill or to specific treatment. The treatment in that case should be accounted for. For coatings based on oxides, instead, the AR material can be assumed to evaporate during the melting process, while in case of landfill it can be assume to leak to ground and soil. Considering that the AR coating is applied only to the laminated pane, it could be considered to previously separate the inner and outer pane of the window and redirecting the inner glass pane to described sorting process.

Option II: AR material is embedded in the PVB. Recycling of PVB is quite rare, so it will not be addressed. In case of incineration of PVB, the oxides AR materials could be assumed to evaporate., while in case of landfill, part of the material is likely to remain in the polymeric matrix of the PVB; however, with a conservative approach, the AR material could be assumed to leak in the soil.

Option III: The adhesive AR film, can actually be separated from the glazing before it is crushed, thus not affecting at all the other components. The film can then be treated as the PVB in option II.

DWS: While the glazing follows the described process, the blinds follow a different path. They are assumed to be transported to a separate treatment facility where the materials are separated and can enter different path. The flow of material for each E-o-L scenario can be taken from EPDs.

Beyond Life Cycle Stage - D (excluded)

This stage takes into account the beneficial outputs of the life cycle of the product. Indeed, all the aspects considered in the other stages were considered to have a damaging effect on the environment, either in terms of resource consumption or in terms of emissions, while in module D the recovery of materials and energy is taken into account.
This section deals indeed with the favourable effect of reusing some by-products, recycling some materials or producing new energy. For the analysed processes this can be correlated with the disposal module C4, specifically for recycling (glass, PVB, blind components) and heat recovery (energy).
However, this module must be handled carefully and coherently with the methodological choices made. The LCA system model defines how to define the relations between products and processes within the life cycle and, according to that, these advantages should be accounted for. The risk is indeed to consider the beneficial effect of reuse/recovering/recycling both at the End-of-Life of the product that generates the new resource (sparing additional emissions as well) and at the product stage of the new product made with ”saved” resources.
Since this analysis aims to evaluate a PSW technology as a product and not to assess its circularity potential, the potential benefits will not be accounted for in this analysis but the recycled materials will be cut-off from the system boundary.

4.2.3. Scenarios

When defining the life cycle of the considered products, some aspects or some processes may be uncertain, either because of the data gathered or because different alternatives are being considered, as it can be for variants of production or End-of-life processes. Since it is not possible to calculate the environmental impact of all these alternatives at once, it is necessary to delineate corresponding scenarios; it is advised to define a baseline scenario to analyse more in detail and to be used indeed as a starting point for the comparison with all the other scenarios. Each analysis produces several data, especially if the contributions of all processes are considered; the manipulation of these data can require some time and still results are quite articulated when several environmental impacts are being analysed. It is therefore advised to focus the contribution analysis on the baseline scenario only, which should therefore be chosen carefully, and to limit the scenarios comparison to the life cycle results, observing if changes occur. As long as these scenarios affect only the embodied stages, it is advised to only analyse the embodied impact results; if the scenarios concern the operational stage instead, as it can be by considering different energy sources or the variation of the energy mix in time, it is advised to analyse the changes in the total impact of the life cycle.

4.2.4. Sensitivity and uncertainty

As assessed in the literature review, the issue of uncertainty is very significant in LCA and, at the same time, it can represent an important complication. Uncertainty is faced already when choosing the LCIA method, which represents an approximation and simplification of the reality; an additional uncertainty is added by the characterisation factors used, which are indeed the result of temporal and geographical approximations. Uncertainty at these levels is usually not addressed especially for technical reasons.

Nevertheless, the uncertainty of the processes in product systems can be addressed more easily. It would be possible to consider some uncertainty for all the parameters included in the calculation, but this would be an excessive caution, especially considering that the calculation of the uncertainty is still not so common in windows' LCAs, and could also lead to final results with uncertainties of excessive magnitude, thus unusable. In addition, especially for LCA, each perturbation of one parameter correspond to a new calculation of the LCI results, so en excessive number of parameters can lead to heavy repeated calculations. It is therefore necessary to select the most significant parameters for the considered product system and for the available data. Based on the background on LCA and on the literature review, the following steps were identified for the calculation of uncertainty in the LCA:

1. Make a contribution analysis of the LCAs: ones the desired scenario is calculated it is necessary to investigate what are the most impactful processes. This cane be done individually for each impact category or, in case the chosen method provides it, though weighting: the results of each process can be normalised, weighted and finally plotted to see which determine the highest impact. While the weighted contribution analysis is quicker and simpler, it is strongly influenced by the normalisation and weighting sets. It is therefore important to still perform the individual contribution analysis for each category, to spot processes that may be impactful only for a specific category and could result more relevant with different sets.
2. Choose the parameters: this must be the parameters that are connected to the most contribute processes. These can be the proportion of some flows i the E-o-L of glazing, the quantity of AR material in the PSW or a distance for a specific transport.
3. Make local sensitivity analysis: normalised sensitivity coefficients (X) can be calculated by perturbing all the parameters (p) and evaluating the magnitude of the results variation on the Impact Scores (IS) for each category. The coefficients are calculated as

$$X_{IS,p} = \frac{\Delta IS_p/IS}{\Delta p/p}$$

   The higher are the values of the coefficient, the higher the effect of the considered parameter is on the LCA and so the more relevant the uncertainty will be in the calculation of the final results.
4. Determine relevant parameters: a threshold for assessing when a parameter is sensible for the calculation shall be set. Following the recommendations of Owsianiak et al., parameters can have a large sensitivity when their coefficient X is higher than 0,5 and a medium sensitivity when it is higher than 0,3.
5. Assign uncertainty to parameters: each selected parameter must be assigned with a specific uncertainty, based on the information available on it. If a series of data is available for a specific parameter, a normal or log-normal distribution can be derived and used to define the parameter.

6. Global uncertainty simulation: the uncertainty of the LCIA results can be calculated through Monte Carlo simulations: these calculated the results for several iteration of the LCA, varying the parameters according to the given uncertainty. The output is the medium value of each impact, and the corresponding standard deviation. The final comparison between the two products shall be based on the comparison between these two result.

Since the calculation of uncertainty in an LCA can be quite time-consuming, especially if its steps are hard to integrate in the LCA software. Therefore, it is advised to calculate the uncertainty only for the most relevant scenarios.

4.3. Energy Simulation

PSW and dynamic window technology are developed and implemented with the aim of reducing the buildings' energy demand by controlling the solar gains, therefore it would be meaningless to compare their environmental impact excluding their effect on the building thy are applied to. This can be done through energy simulations, estimating the expected energy demand of the building with each of the considered technologies.
Even though energy simulations are an extremely common practice in the building sector, their application and integration to the LCA of windows is significantly less common since it introduces several additional parameters and, with them assumptions and uncertainty. These may depend mostly on the modelling, concerning building, context and climate, and on the definition of the contribution to the LCA.

4.3.1. Modelling

The modelling approach for buildings utilizing PSW and DWS window technologies is contingent upon the study's specific objectives. In instances of real projects, where the location, geometry, and properties of the building are well-defined, the modelling process becomes more straightforward. Conversely, when conducting a more generic evaluation, additional considerations come into play.

Opting for office or commercial buildings is advisable due to their frequency and the advantages they offer in terms of occupancy modelling. The office setting, being a common application, facilitates a more regular modelling approach.

When defining the building's location, it is necessary to align it with the geographical scope outlined in the Life Cycle Assessment (LCA) scope. Consider climate variations between locations and note that PSW may yield more promising results in hotter climates. However, a conservative approach is recommended to avoid overemphasizing the benefits of PSW in climates that excessively favor its performance.

The choice of the simulated space's size, whether a room, floor, or the entire building, should be based on the functional unit specified in the LCA scope. In the case of a single window, focus on modeling a single room with adiabatic internal walls, ceiling, and floor, where the facade with the window represents the only surface of heat exchange withe the outdoor space. In case the functional unit is the whole facade, then it is advised to simulate the entire building and include the internal partitions or at least the internal mass, to limit the uncertainty in the results (Silva et al. 2014).

Consideration of local regulations and building practices is crucial, encompassing properties of the opaque wall facade, particularly the WWR, the U-value, temperature set-points, lighting requirements, and ventilation, occupancy schedule and loads. Furthermore, automated regulation of lighting should be accounted for, recognizing that both PSW and DWS technologies may lead to a decrease in daylight to be compensated by artificial lighting.

Auto-Responsive glazing

The modeling of the AR material transition is determining to reach a meaningful results when comparing the the technologies since it consists in the only difference in the energy simulation. Depending on the software used for the energy simulation, a more or less articulated implementation of the AR transition may be possible. In general, it is important to model and discern the main optical properties τ_{sol} , $\tau_{\text{vis}}$and, if possible, τ_{NIR} since they affect differently the heat gains and the lighting needs. Another more precise option consists in defining optical spectrum the glass, assigning transmittance, reflectivity

and absorbance to the desired frequency bands, as it can be done in EnergyPlus.
The change in the AR glazing properties should take into account its transitional range and avoid unrealistic sudden change in the properties from clear to fully tinted state. This is especially important when modelling thermochromic windows, since their transition is usually slower and does not necessarily reach the fully tinted state but often stops at one of the intermediate states. Three main approaches were identified to define these intermediate states:

1. assumed linear transition
2. assumed sigmoid transition
3. transition from specific data

Linear transition: this first option is the simplest one to model and it assumes a uniform transition from the clear to the tinted state of the window. It requires the properties of the clear and tinted state, including the corresponding values of the stimulus (temperature or solar radiation), and the umber of intermediate states. these are then calculated with a simple interpolation.

Sigmoid transition: this modelling approach, suggested by Arnesano et al. (2021), provides a smoother transition curve, more adherent to the real effect of the properties transition of Photochromics and Thermochromics. The transmittance of each intermediate state with temperature T_i depends on the temperature range and on the optical properties at clear and tinted state, but also on the chosen slope coefficient a, according to the formula:

$$\tau_i = \frac{\Delta\tau}{1 + e^{a(T_i - T_c)}} + \tau_{min}$$

However, the chosen slope coefficient should suitably approximate the curve, so that the transition happens mostly in the transitional range. An illustrative comparison between linear and sigmoid transition is shown in figure 4.8.

Specific data: sometimes, suppliers or developer of PSWs experimentally calculate and provide precise data for their products. When available this option can be preferable, being supported by more solid data.

In general, according to the literature review, seven intermediate states were considered sufficient to describe the transition of the PSW. It is important to point out that the level of detail of the transition modelling should be coherent with the simulation time steps and with the level of detail of the rest of the model: it is not necessary to use extremely specific data if the building model includes several approximation and if the simulation time steps are quite large.

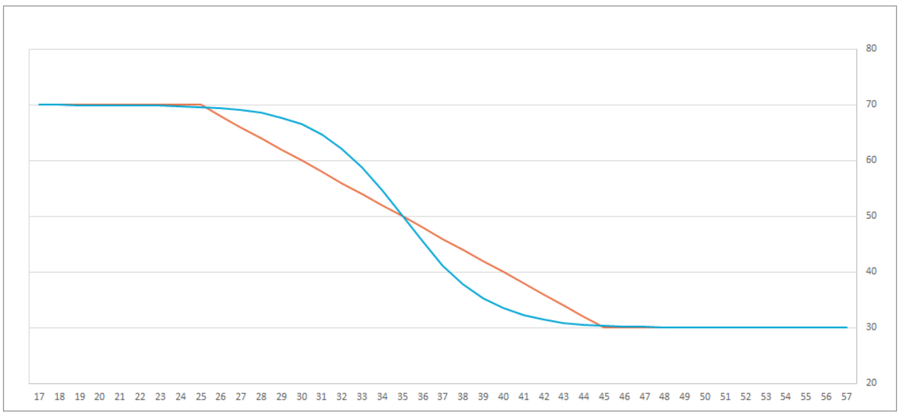


Figure 4.8: Two examples of transition in the range from 25 to 45 °C, on the horizontal axis: a linear curve (orange) and a sigmoid curve (blue), with a slope coefficient of 9,4/20

The temperature transitions is subjected to hysteresis, meaning that the material follows a slightly different behaviour in the transition from clear to tinted and vice versa; this is often hard to model in the energy simulation software (Favoino, Giovannini, et al. 2017), so it cannot be easily implemented in the modelling of the window.

4.3.2. Glazing and benchmark

In general, the glazing can be expected to consist of a DGU with laminated external pane and with low-e coating on the inner pane. As specified in the LCA Goal, the PSW is being compared to a dynamic window system, thus a static window with a dynamic sun-shading component. Unless a specific static window is being considered as an alternative to the PSW, the glazing static window should be as similar as possible to the glazing of the PSW, except for the AR layer, in order to provide the two compared products with similar thermal properties, in particular the U value.
The specification for the sun-shading element should align with the considerations outlined in the Life Cycle Assessment (LCA). Depending on the specific study, there are several options to explore, but generally, blinds, especially indoor ones, are often regarded as the most prevalent choice. The energy simulation requires to define two aspects that are only partially addressed in the LCA: the optical properties of the sun-shading component and it activation mechanism. When considering a passive shading device, this is most probably activated manually and can be simulated by implementing occupants behaviours in the model.

4.3.3. From Energy simulation to Operational energy use

Including the operational energy in the LCA is not a common practice: most of the studies analysed in the literature review prefer to consider the energy demand of the building as a separate category in the LCA, thus leaving the comparison issues unresolved: a PSW is expected to give a lower operational energy than a static window, and thus a lower operational impact, while the embodied impact is expected to be lower for the static window. Segregation of embodied and operational impact in different categories doesn't allow a numerical comparison, which is instead possible if the operational impact is integrated in the LCA.
However, the integration of the operational impact in the LCA can increase the level of uncertainty of the calculation. First of all, it is difficult to determine what output should be chosen between the energy demand of the considered space and the energy use, which depends on the systems used. Besides this issue, the energy demand of the building does not depend on the window only, but also on the opaque facade and on the ratio between facade and room volume. It can therefore also be discussed if the whole demand should be used or if only a fraction of it and what fraction.

Output choice

When considering the type of output to use, energy use is the most realistic option. This choice is suitable especially for studies concerning a specific building, where the systems for cooling and heating and their efficiency coefficients (COP and EER) are defined. However, this is more difficult when considering a generic building: indeed, the values for these coefficients can vary significantly, since they depend on the several components of the heating system and of the cooling system. The energy demand instead identifies the energy needed for keeping the indoor conditions with an ideal system and is therefore lower than the energy use. Even though it underestimates the actual amount of energy to be included in the LCA, the energy demand can be used as input under the premise of a conservative approach: the choice of a lower operational energy indeed penalises the PSW result, whose operational impact is indeed lower on an absolute value compared to the static window.

Window contribution

The contribution of the window to the overall operational energy is quite hard to determine. Two main approaches can be considered: attributing the whole energy needed for the building as operational energy or making a subtraction with a baseline value. The option of the full attribution of the energy to the window is compatible with using the whole results of the embodied impact, but it gives

very high values for the operational energy that include the effect of other components as well, such as the opaque wall. The baseline-attribution approach instead, shows only the decrease or increase of the operational energy, and requires a baseline value to be used for both the compared technologies, which can be the static window without sun-shading. This approach, however, reduces the magnitude of the Operational energy and, even though the parameters used still influence the result, this is reduced and made less evident.
It is very important to point out that the approach chosen for attributing the operational energy to the window determines how the final assessment of the LCA will be carried out: if the full-attribution approach is chosen, the corresponding operational impact will be summed to the full embodied impact of the corresponding product system. If the baseline-attribution approach is used, the operational impact variation will be summed to an embodied impact variation; therefore, in this case, the embodied impacts of the baseline technology used in the energy simulation must be calculated and subtracted from the embodied impacts of both the PSW and the dynamic windows system.

4.4. Life Cycle Impact Assessment

The aim of this calculation is to determine the total impact variations related to the use of PSW and DWS, thus calculating the impact of PSW, DWS and StW, used as benchmark technology. However, the calculation of the total impact variation is seen as the final union of operational and embodied impact; since it is not common practice to include the operational energy use in LCA of building components, it is advised to initially maintain the distinction between Operation and Embodied impact.
First of all, the Operational energy must be determined through the results of the energy simulation, accordingly to the choices made in terms of energy output and window contribution approach. More scenarios can be considered and the uncertainty can be defined accordingly. The operational impact must then be calculated by multiplying the chosen energy output for the lifespan of the study and characterising this result, choosing energy generation processes according to the energy source assumed for the case.
The embodied impact consists in the characterised results of the modelled Life Cycles of PSW, DWS and StW, giving the associated environmental profile. These always be reported in the study. The results of different impact indicators have their unit and are not comparable, therefore, it is advised to also normalise them relatively to the StW: the results for each impact would then be expressed in as percentages, allowing an easier comparison and interpretation. It is advised to address the embodied stage following these steps:

1. calculate the chosen baseline scenarios for each product
2. separate the results by stage and then by processes, to allow the contribution analysis
3. calculate the defined sets of scenarios
4. calculate the results for the perturbed parameters of the sensitivity analysis
5. perform the Monte Carlo Simulations

The results of the Monte Carlo simulation can be considered more reliable than the baseline scenarios since they take into account the effect of possible variations in parameters. If this is performed, its results shall be used for the calculation of the total impact instead of those of the baseline scenario.

The final step consists in joining the results of embodied and operational impact, depending on the attribution approach chosen. If the full-attribution approach is chosen, the operational impact and embodied impact are simply summed:

$$IS_{tot} = IS_{Op} + IS_{Emb}$$

If the baseline approach is used, the impact variations with respect to StW shall first calculated and then the sum of the operational and embodied variations, obtaining:

$$\Delta IS_{Op,PSW} = IS_{Op,PSW} + IS_{Op,StW}$$

$$\Delta IS_{Emb,PSW} = IS_{Emb,PSW} + IS_{Emb,StW}$$

$$\Delta IS_{tot,PSW} = \Delta IS_{Op,PSW} + \Delta IS_{Emb,PSW}$$

A negative total impact variation means that the assessed technology has a lower impact of the baseline technology StW. If more technologies are being compared, as it happens for DWS and PSW, an inferior total impact variation indicates a technology with a lower impact.

4.4.1. Weighting and normalisation

As aforementioned, is useful to show the variation of the environmental profile from different products or for different scenarios. The use of several impact categories helps in determining with higher precision the variation in the environmental impact. However, monitoring several impact categories during an analysis can be quite complex and confusing.
The external normalisation and weighting of the results can be useful at two levels. Firstly, it provides a End Score that can be used as a single indicator for the overall environmental impact. Secondly, the contribution of the considered indicators to the End Score which categories impact the most on the result and, therefore, which categories can be more meaningful to observe.

4.5. Interpretation

The interpretation step concerns the analysis of the obtained results to derive conclusions of the study. First, the impact and their contributions are analysed to identify the most significant issues, thus the key processes and assumptions for the calculated systems; this is mainly done through the contribution analysis and the scenarios comparison. During this operation, the consistency and the completeness of data shall be checked, especially between different systems. If some data are taken from different sources, different system boundaries or allocations rules may have been considered or the data may have different qualities. This can be expected for example for data derived from EPDs or from data modelled by the LCA practitioner; where possible, these inconsistencies shall be corrected in the inventory and in the calculation, and otherwise they should be clearly stated. As anticipated, the sensitivity of uncertain parameters shall be checked and assessed as well.
Finally, the conclusions of the study shall be drawn based on all the significant issues and on the checks executed on the data, pointing out the limitations of the study. This should entail the observation about how the two technologies impacted each category and what were the main reasons for their differences the lowest environmental impact. in line with the specific goal of the study, recommendations shall be provided both on the improvement of the consistency of the study and on the meaning of the result themselves.
More detailed indications are given reflecting the structure of the results presented in the previous sections.

Simulation results

The results of the energy simulation, not being the results of an LCA analysis, cannot be interpreted as explained above. However, it is relevant to focus on the effect of the products on the different energy demands, thus lighting, heating and cooling, observing how each technology affects them. It is important to observe if the result for each demand correspond to the expectations and what could be the reasons when it is not the case.
In general, PSW are expected to increase the demand for lighting compared to StW, while the should cause a decrease of cooling and an increase of heating. Similar variations shall be expected for the DWS, since it is supposed to be used for the same purpose as PSW. If reference values from other studies are available for the simulated products, it is advised to compare them.

Embodied impact

Concerning the embodied impact, a more extensive analysis is needed. If an internal normalisation is performed, it is important to maintain always the same set of results as baseline for the calculation and to specify when a different reference is used. An ideal reference could be the results for the static window StW for the baseline scenarios. The first step consists in the analysis of the baseline results. When weighting is applied, this step can also include an analysis of the contribution of the different

indicators to the End Score and, if few categories determine most of the impact, the focus of the rest of the analysis can be on those. The stage and process contribution shall be aimed to identify what aspects of the life cycle have the highest impact on the results and to determine if their contribution differs significantly depending on the observed category.
Within the contribution analysis it is important to distinguish between the processes that are common to the compared products, usually those related to the StW such as the glazing production, and those that characterise the PSW and the DWS, such as the production or the End-of-Life of the AR material or of the sun-shading device. This analysis is quite detailed so it is advised to perform it only for the baseline scenarios.

The previously defined set of scenarios can then be compared comparing and, when noticeable variations between their impacts are identified, the cause for that variation shall be investigated, to determine the parameter or parameters that are the cause of it. This can be done by observing variation in the processes affected by the new scenario , also through Sankey diagrams: these represent the tree structure of the product system adding the impact caused by each process and the flow of this impact with the linked processes.

The sensitivity analysis should be performed on parameters of high relevance identified through the contribution analysis, if those present a high uncertainty as well. The normalised sensitivity coefficients allow to easily select those parameters that have a sensible effect on the embodied impact and that should therefore be involved in the uncertainty calculation.
The results of the Monte Carlo simulation for the different product systems shall than be compared if the observations made for the baseline scenarios changed and how, also considering the uncertainty ranges.

Total impact results

The total impact shall be calculated and discussed according to the chosen attributional approach. The results for PSW and DWS must be compared to the baseline window StW to determine if they provide a reduction of the overall environmental impact and which of the two gives the lowest impacts. It is then important to analyse and discuss the contribution of embodied and operational impacts within each product system, to determine the reason for the calculation and possible flaws to be improved.

5
Case Study

5.1. Introduction

In this section, the methodology is applied to a specific case study, in order to give a practical example of its application. Here all the methodological choices and assumption made for the calculation of the operational and embodied impact are explained. The results of the calculations are instead presented and discussed in the next chapter.
COncerning The chosen technology is Suntuitive Low-Iron with 3 low-e coatings, a thermochromic DGU developed by Pleotint LCC (Pleotint 2019); the thermochromic layer is integrated as interlayer of the laminated external pane. For this product, data about the performance in the use phase were found, but it was not possible to gather the necessary information about the production method and its impact, mainly due to confidentiality reasons. Therefore, the processes needed for the production of the PSW will be based on the information gathered in the methodology and on the data provided by Sirvent et al. (2022).

5.1.1. General considerations on the window

Glazing build-up

Table 5.1: Build-up of the Auto-Responsive glazing (left) and the static glazing (right)

Layer	Thickness (mm)	Weight (kg/m^2)
Clear Glass	5	11,9
Suntuitive interlayer	1,22	1,4
Clear Glass	6	14,2
Argon Gap (90%)	11	-
Low-e Glass	6	11,9
TOTAL	29,22	39,4

Layer	Thickness (mm)	Weight (kg/m^2)
Clear Glass	5	11,9
PVB layer	0,76	0,9
Clear Glass	6	14,2
Argon Gap (90%)	11	-
Low-e Glass	6	11,9
TOTAL	29,22	38,9

The AR glazing is modeled as described by the producer in the commercial brochure (Pleotint 2019); this also provided some of its properties, namely $\tau_{vis}$and SHGC for the clear and tinted state, and the U value. Theoretically, the benchmark would only differ for the interlayer, which would be a standard 0,76 mm PVB instead of the 1,22 mm of Suntuitive interlayer. while the glass panes and the cavity would be identical in terms of thickness and properties. In practice, it was not possible to model explicitly the two glazing types in this way, due to some constrain in EnergyPlusend in the LCA data; however, the modeling was as close as possible and is explained in the respective sections.

Window areas

In the LCA, it is important to distinguish between the visible area A_{vis} and the real area A_{real}. A_{vis} indicates the surface of the glazing that actually allows the transmission of light and is used both as a reference unit of the LCA and is the area used in the energy simulation. A_{real} is instead the real area of the glazing, thus the one used for calculating the amount of material used at every stage and the difference between the two is the glazing area hidden by the window frame. For simplicity, A_{real} is assumed to be higher 6% higher than A_{vis}.
The frame area is calculated as well as a function of $A_{vis} \times f_{frac}$, where f_{frac} is the frame fraction, chosen as 25 % based on the values used in the standard EN ISO 10077-1:200 (International Organization for Standardization 2020)

Dynamic Window System

For the comparative analysis, a term of comparison must be chosen. Rather than using a static glazing, as most studies on PSW do, it seemed more appropriate to use another dynamic building element, defined as Dynamic Window System (DWS), so a static window with a dynamic component. Among the solar gain control systems currently widely applied, indoor blinds were identified as the most suitable choice: first of all, they are significantly more common than other shading systems, such as overhangs, fins and louvres; these are used rarely and are often static. External blinds are also not extremely popular and are exposed to outdoor perturbations, wind especially, thus requiring stronger substructure, higher maintenance and still undergoing higher chances of malfunctioning. Finally, as the PSWs, internal blinds can be considered passive, if manually activated and imply a reduced amount of additional components, unlike the alternatives.
The DWS thus consists of two distinct elements: the blind and the static window (StW). Since the focus of the research is the comparison of the effects of the dynamic behaviour of PSW and DWS, it is relevant to highlight their difference by removing, as much as possible, the effect of their static component. Therefore, StW was used as benchmarking technology used for both PSW and DWS.

5.2. Energy simulation

The energy simulation was carried out through EnergyPlus, a widely known and used energy simulation software developed by the U.S. Department of Energy's Building Technologies Office. The output of each simulation consists of the yearly energy demand for lighting, heating and cooling for the specific model and conditions simulated.

5.2.1. General model

The simulation model is identical for all the tested window systems and is based on the ASHRAE office standard. It consists of a rectangular office room with a depth of 6 m and a facade, 8 m wide and 2,7 m tall. All the surfaces are adiabatic besides the south-oriented facade, which consists of the window and an opaque wall; the insulated brick and concrete wall has a U value of 0,295 W/m^{2}K, fulfilling the requirements for new buildings according to the Dutch building code Bouwbesluit (Rijksoverheid van Nederland 2012). The window is placed at a height of 0,8 m from the floor surface and its visible surface is 6,4 m wide and 1,5 m tall, for a total surface of 9,6 m^2 and a WWR of 44,4%.

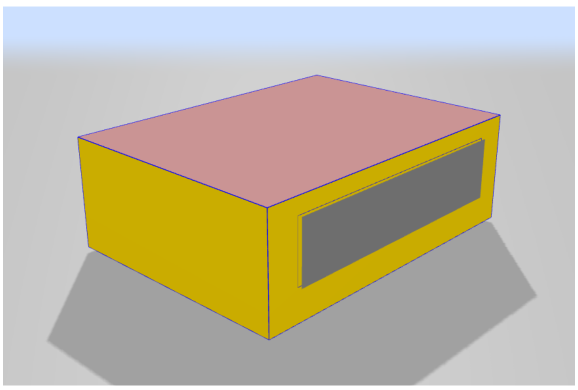
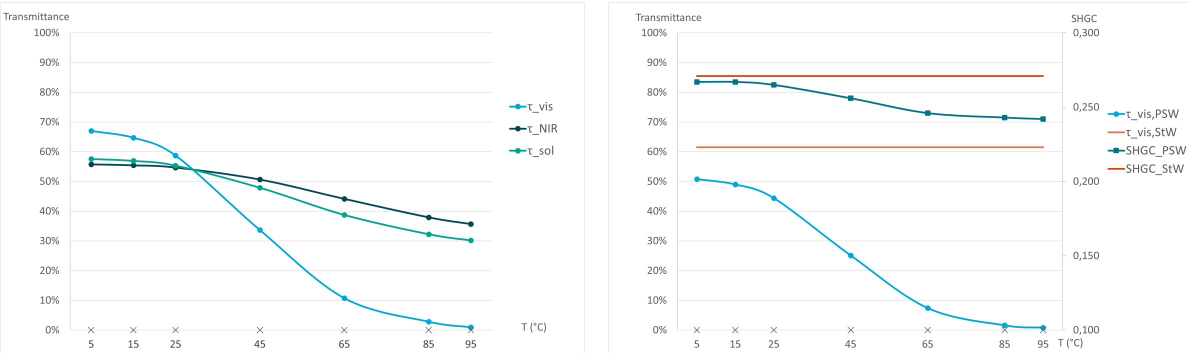


Figure 5.1: 3D view of the energy simulation model in EnergyPlus

All systems and internal gains are modeled are active only when the building is occupied, thus 5 days a week between 8:00 and 18:00. The occupants are quantified through a density of 0,11 people/m^2 and a sedentary metabolic rate of 126 W/person, while the equipment's load density is 11 W/m^2. The lighting has a load density of 6,5 W/m^2 and is set to maintain a minimum light intensity of 500 lux at a reference point, positioned in the middle of the room at a height of 0,8 m. The HVAC System is an ideal full air system automatically sized based on the climate of Amsterdam and the thermostat set-points are 19 °C and 26°C. An infiltration of 1,44 V/h is assumed. Coherently with the LCA choices, Amsterdam was chosen as the location for the simulation, taken from the corresponding EPW file.

5.2.2. Glazing modelling



(a) Suntuitive glass pane transition: τ_{vis}, τ_{sol} and τ_{NIR} , calculated as averages of their respective range.

(b) Comparison of $\tau_{vis}$and SHGC for PSW and StW

Figure 5.2: Behaviour of the modeled glazings with Surface temperature variation

The glazings were modeled in EnergyPlus as *Construction*, by defining each glass pane through *WindowMaterial:Glazing* with data taken through WINDOW7.8 from the IGDB, International Glass Database, which provides detailed spectral data on commercial glass panes. The cavity and the internal low-e pane were identical for both PSW and StW, while the laminated pane, which had to be defined as a single pane, differed. The glazing of StW and DWS are identical.

Pleotint uploaded the spectral data for 7 transitional states for Suntitive laminated thermochromic pane. These were downloaded from IGDB version 80.0, which contained the most updated data. Indeed, this product was first added to IGDB in 2013 (version 31.0) and removed in August 2021 (v.81). These official detailed data, since available, were preferred to linear interpolation since they were considered more precise for simulating the variation of the glazing properties, both across the temperature range and across the light spectrum. In the EnergyPlusmodel, the thermochromic laminated pane "Suntuitive_IGDBv80" was modeled pairing all its transitional states with the corresponding temperature, respectively 5, 15, 25, 45, 65, 85, 95 °C, shown in 5.3; these laminated panes were exported singularly to EnergyPlusand used to model one single dynamic pane in *WindomMaterial:GlazingGroup:Thermochromic*.

Table 5.2: Properties of the glazing in EnergyPlus, calculated through WINDOW7.8

	AR glazing	**Static glazing**
EnergyPlus name	PSW_SuntuitiveIGDBv80	BEN_window
U value	1,327 W/m^{2}K	1,332 W/m^{2}K
τ_{vis}	0,508 (clear, for T=5°C)	0,615
SGHC	0,267 (clear, for T=5°C)	0,271

The static laminated pane for the StW was chosen among the commercial options available to give a similar U value to the overall glazing, calculated on WINDOW (table 5.2). The two glazing were finally built in EnergyPlus as shown in table 5.3.

Table 5.3: Layers of the AR glazing model in EnergyPlus, with respective ID from WINDOW7.8 . For *Suntuitive pane*, the IDs of all the transitional states are reported.

	AR glazing			**Static glazing**		
Layer	**Name**	**t (mm)**	**ID**	**Name**	**t (mm)**	**ID**
Laminated glass pane	*Suntuitive pane*	12,6	16500/ 16506	C_Lam66.1.grd	12.0	3080
Gap with Argon	Air (10%)/ Argon (90%)	11,0	9	Air (10%)/ Argon (90%)	11,0	9
Low-e coated glass pane	LoE³ 366 on 6mm Clear	5,7	2157	LoE³ 366 on 6mm Clear	5,7	2157

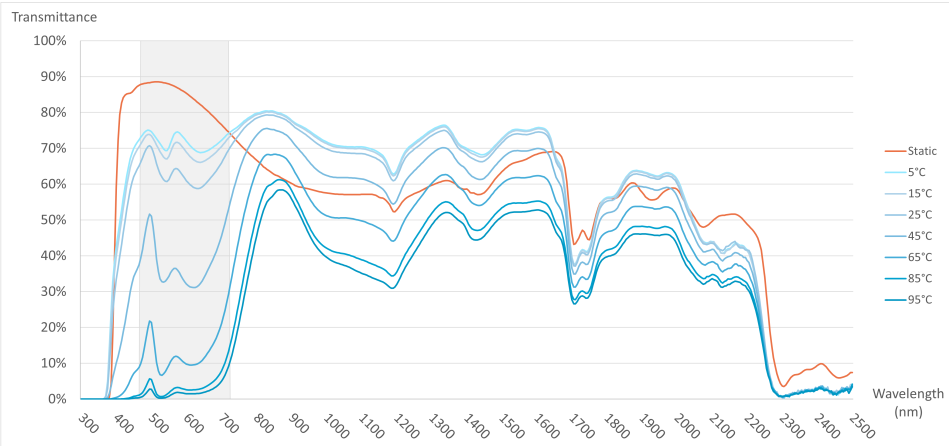


Figure 5.3: The transmittance of Suntuitive through the solar spectrum, in the different transitional states, as exported from IGDB. The grey areas define the visible range (dark grey) and NIR range (light grey).

Blind modelling: The dynamic component of the DWS consists of a manually activated indoor blind. The manual activation does not require energy consumption, thus making the DWS a passive system. This activation depends on the interaction of the users with the blinds, which follows the stochastic behavioral model developed by Haldi and Robinson (Haldi et al. 2009). The optical properties of the blind are based on the data of a product GreenScreen Eco - openness factor 3% - White (HunterDouglas n.d.).

Table 5.4: Optical properties on the blind as defined on EnergyPlus

τ_{sol}	ρ_{sol}	τ_{vis}	ρ_{vis}	ϵ_{IR}	τ_{IR}
0,47	0,44	0,39	0,4	0,12	0,46

Output and contribution in LCA

Following a conservative approach, the chosen output of the energy simulation were the energy demands of heating, cooling and lighting. The energy demand was preferred to keep the building model as generic as possible, thus avoiding the definition of energy sources and distribution systems.

$$En_{PSW} = En_{h,PSW} + En_{c,PSW} + En_{l,PSW} \tag{5.1}$$

Regarding the integration of the Operational energy with the Embedded energy in the whole LCA, a baseline-attribution approach was chosen, using StW as baseline technology for PSW and DSW in both sections of the LCA. In addition, the energy model consists of a single room with one window of the same size of the window considered in functional unit of the LCA. As a consequence, the whole energy demand of the room was attributed to each of the simulated windows, thus PSW, DWS and StW. When finally comparing the whole life cycles of PSW and DWS, the relative impacts were used, both for the embodied and the operational stages of the life cycle, calculated subtracting the results for StW from the results for PSW and DWS.

$$\Delta En_{PSW} = En_{PSW} - En_{StW} \tag{5.2}$$

Since an ideal full air system was used for the simulation, the energy demand was assumed to be provided entirely from the electric network; this was implemented in the LCA by using the product between total ΔEn and the lifespan (45 years) as input for the process *"market for electricity, low voltage - NL"* from Ecoinvent (Swiss centre for life cycle inventories 2022), based on the data of the *IEA – International Energy Agency* (n.d.) from 2018 (figure 5.4).

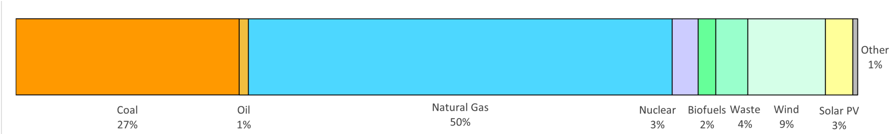


Figure 5.4: Electricity mix of the Netherlands in 2018, according to the database of IEA

Uncertainty of Operational Energy

The values obtained from the energy simulations derive are subjected to uncertainty, due to the simplifications introduced by the modelling and due to the differences between the assumed behaviour of the building and the real one.
The research by Silva et al. (2014) determined that the geometrical simplification of buildings underestimates the energy demand, but this is to be ascribed mainly the neglecting of internal mass and thus a change in the heat storage of the building.
A study by Li et al. (2023) analyses several sources of uncertainty in the LCA of buildings, assessing how the fluctuation of the operational energy due to the services can range between 11 and 33% of the estimated value. For the total energy demand simulated, an uncertainty of 15% will be therefore used to estimate the uncertainty of the obtained results.

5.3. Life Cycle Assessment

Description of specific choices and changes in this model, compared to methodology.
Full LCA of the selected product, including integration of the simulation results.
Description of results and discussion

5.3.1. Goal

Goal

The goal of this study is to compare the environmental impact of a PSW with AR interlayer and a static window with indoor manual blind (DWS), in order to assess which of the two has a higher embodied impact and if the savings in the operational impact compensate for it in the calculation of a total impact, in relation to a benchmarking static window.

5.3.2. Scope

Functional unit

So the functional unit is to close a surface of 9,6 m^2 of an office facade while providing standard building envelope performances, allowing daylight and controlling solar gains without active consumption of energy for the lifespan of the whole facade system. The reference flow is a window with a visible area of 9,6m^2 .

System boundary

The system boundary, as for the methodology, defines a cradle-to-grave LCA, considering the modules described in the methodology for option II, so with the AR layer applied as interlayer on the external pane of the DGU with laminated panes. A cut-off system model is used. The system boundary of the two product systems is illustrated in figure5.5

LCIA Method

The chosen LCIA method is Environmental Footprint (EF3.1). This method is developed by the JRC of the European Commission with 16 environmental categories. This ensures the reliability of the LCIA method and a satisfying broadness of assessed impacts. The most recent standard for the redaction of EPDs in the EU (EN15804+A2) is based on the same main impact categories, thus allowing the use of EPDs' results in the study, specifically for blinds. In addition, EF3.1 is provided with a normalization set (Andreasi Bassi et al. 2023) and a weighting factors, allowing to calculate a Single Score for each scenario of the product systems and quickly compare them. According to the interviews results LCIA method EF3.1 and the corresponding also used in the industry for the LCA of building elements.

Characterisation: Some of the 16 main categories of EF3.1 are provided with sub-categories, which are expressed with the same unit but provide a more detailed distinction on the impact. The main category is the sum of all its subcategories. These categories are:

- Climate Change (GWP): fossil, biogenic and land use
- Ecotoxicity, freshwater (ETP): organics and inorganics
- Human toxicity, carcinogenic (HTPc): organics and inorganics
- Human toxicity, non-carcinogenic(HTPnc): organics and inorganics

Since the EN15804+A4 does not require these subcategories, they are not assessed in the EPDs. Since the sub-categories are not involved in normalization and weighting and would have been incomplete due to the use of EPDs, they were neglected.

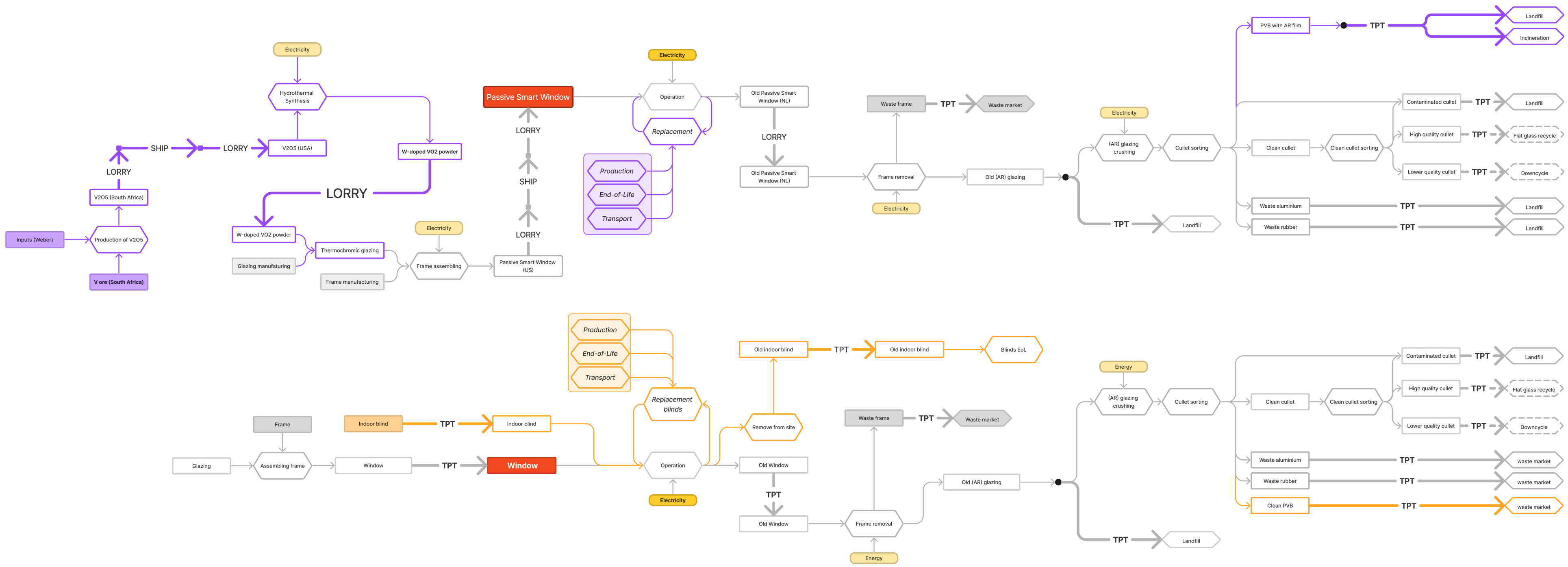


Figure 5.5: System boundary of Suntuitive and the benchmark. The diagram represents contemporary the two compared product systems: products are represented in rectangles and processes (including End-of-life) are represented in hexagons. Grey represents the processes and products that are common to both the product systems, purple represents the PSW and orange represents DWS. The elements of background products and processes are filled.

Normalization and Weighting: EF3.1 imposes the calculation of a final Single Score, by providing sets of normalisation and weighting factors. Those were not directly implemented in the downloaded material for OpenLCA, so it was necessary to research for these data. Since the EF method bis developed by the JRC (Joint Research Center for the European Commission), the ire repository was consulted.. in general, it was noticed how several documents are continuously produced and how the information can often be spread on different documents as well. For example, the latest update of Environmental Footprint EF3.1, including both LCIA method and database, was released in July 2022, while the corresponding Normalization Factors set was published separately the following year (Andreasi Bassi et al. 2023). At this moment, an updated Weighting Factors set is not yet available, thus the previous set is used 2018. These weighting factors are defined as the combination of weighting sets resulting from different approaches, with the aim of considering different criteria and stakeholders .

These two set of factors refer only to the 16 main categories of EF3.1, so the sub-categories were assigned with the same NF of the corresponding main category but with a null WF.

The NFs used were evaluated per person based on the global population in year 2010, thus 6895889018 persons (6,89 bn), without being updated to the new world population, that increased of more than 15,6%, reaching 7,98 bn by the end of 2022 (last available data).

Software and data sources

The data used for this study are taken from the database Ecoinvent (Swiss centre for life cycle inventories 2022), among the widest and most popular LCA databases, both for the construction and the chemical sector. From this database, both transformation activities and market activities were used. The data referred to the blinds of the benchmark are taken from an EPD (Epddenmark 2023), while the production of the AR compound (W-doped VO_2 powder) was taken from the literature. The software used is OpenLCA: this a reliable free software, so available without the use of a license, and is compatible with Ecoinvent and with the most popular LCIA methods.

5.3.3. Life Cycle Inventory analysis

It was not possible to retrieve the data related to the specific production of Suntuitive, mainly due to contact issues and confidentiality. The thermochromic interlayer is assumed to be a PVB film coated with W-doped VO_2 powder, as described by Sirvent et al. (2022).

All the processes used in the LCA are reported in the appendix A: the processes modelled or adapted are reported with all input and output, while the processes taken directly from Ecoinvent are listed and referenced to the original database.

Glazing

The glazing consists in a laminated safety glass with a special interlayer, which integrates the AR material. This is assumed to be Vanadium dioxide VO_2 and is assumed to be embedded in the PVB during its production Since Pleotint, supplier of Suntuitive, is located in Grand Rapids, Michigan (USA) the AR layer is assumed to be produced in the same location and to be laminated in glazing production site within the same geographical area, the facility of Cardinal Glass in Fremont, Indiana. For the rest, all processes and materials involved in the manufacturing of the AR glazing are identical to those of the static glazing of the benchmark. The same can be said about the installation and removal on site and about the transportation, both in terms of weight and routes.

Transport

All transport on land are assumed to be made on diesel trucks, at all the life stages. For USA and South Africa, the lorries class is unspecified, while the Netherlands an EURO6 lorry was specified, to comply with the local regulations. The truck distances for the production of V_2O_5 until the delivery to the port of Duncan (South Africa), are drawn form the source studies (Weber et al. 2018; Sirvent et al. 2022), while the other transportation routes were calculated with Maps.Google.com, concerning the transportation on land, and with SeaRates.com, concerning the transportation on sea. The specific locations were considered to estimate the transportation

Vanadium dioxide layer

The vanadium dioxide (VO_2) in the interlayer is manufactured starting from Vanadium pentoxide (V_2O_2); no specific data for this compound are available on EcoInvent, so it is necessary to deduce information from other studies. Sirvent et al. (2022) refer to the work of (Weber et al. 2018) who investigate the LCA of a V_2O_5 based battery. The impact of the process will be therefore drawn from that study. The study assumed the extraction and manufacturing to take place in South Africa and composes of five subsequent processes. The processes from Weber et al. (2018) were replicated, with updated data, in order to calculate the data for production of V_2O_5, keeping, for each flow involved, the same quantities. Concerning the elementary flows, two assumptions were made: The emissions to water were all reported as unspecified, due to lack of further indications; the emissions to air were assumed for an area of low population, based on the location of the manufacturing processes, Evraz Highveld Mine, and on the indication of the Ecoinvent guidelines (Weidema et al. 2013). The production of VO_2 was instead adapted to the geographical context of USA, also updating the Ecoinvent data. The LCIs of all processes are reported in the Appendix A.
Given the considerations form the interviews, at the moment there are no technologies aimed to remove the VO_2 from the PSW. Similarly, there is no system developed to collect the used material and even less for recycling it, so the compound is assumed to remain on the plastic layer it is applied to and to follow the same EoL, so either incineration or landfill. However, the impact of the EoL of Vanadium composites is hard to estimate: on one hand, it is not included in Ecoinvent database and the sources for vanadium compounds production (Sirvent et al. 2022; Weber et al. 2018) assume it as an inert waste when disposed, or assume it to be fully recycled. On the other hand, the environmental impact of Vanadium and its composite cannot be neglected, since they is characterised in LCIA methods: in EF3.1, vanadium's emission affect all typologies of Eco-toxicity and is accounted as cause of non-cancerous Human Toxicity. However, this methods in Ecoinvent characterise vanadium flows only as element, ion or vanadium composites, generically defined, but not specifically vanadium dioxide. Even though the precursor of VO_2, V_2O_5, is more widely studied, mainly due to its application in recyclable batteries, no data were found in literature about VO_2. Due to this, the compound is assume to leak in the soil in case of glazing landfill and to evaporate in the air in case of sorting of the glazing waste.

Modelling of the Life Cycle

The life cycle of the considered products was modelled following a centralised supply chain: the division in life stages was used to separate the life cycle and manage its different parts with more agility. This helps, for example in accounting for the replacement, which consists in the sum of other modules, or for accounting for common identical processes, without the need to model them twice.
The considered life stages were:

- A1-3: Product Stage
- A4-5: Construction Stage
- B4: Replacement Stage
- B6: Operational Energy
- C1-4: End-of-Life Stage

The product life cycle is assessed by calculating each stage in parallel and gathering them in the complete life cycle of the product, as illustrated in figure 5.6. This allows to calculate the impact of the whole life cycle of the product but, at the same time, to clearly distinguish the impact of each life stage. This also allows to easily include the replacement stage as the repetition of the other stages.

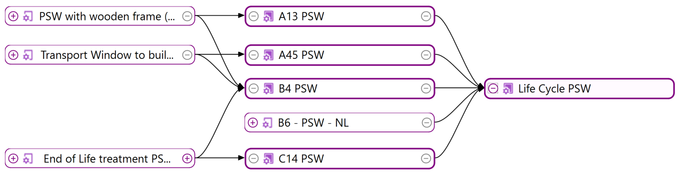


Figure 5.6: Structure of the PSW life cycle modelled in LCA

Blind

Due to the lack of data about blind's impact on Ecoinvent, their environmental impact was taken from an EPD (Epddenmark 2023). As the figure 5.7 illustrates, the EPD did not cover all the life cycle modules. Moreover, it considered a manual, therefore null, impact for the installation and uninstalling of the blind on the window (A5 and C1); the impact of the transport to the building site A4 was not reported and neither was the Use stage B. The impact of module D was reported in the EPD but left out from the performed LCA, coherently with the declared boundary system. The impact for each category was imported as processes with the following steps:

1. Fictitious elementary flows were created, one for each impact category of the LCIA.
2. Flows were characterised for their respective category with a factor of 1.
3. For each life cycle module assessed in the EPD, a fictitious process was created with no inputs.
4. In each of these processes, all 16 fictitious elementary flows were added, with a value corresponding to the EPD's impact score for that category.
5. The data of the transport from building site to a local recycling facility, C2, were ignored
6. The transport stages A4 and C2, both depending on the lcoation, were redefined as truck transport on an assumed distance.

Life cycle stages and modules (MND = module not declared)																	
Product			Construction process		Use							End of life				Beyond the system boundary
Raw material supply	Transport	Manufacturing	Transport	Installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction demolition	Transport	Waste processing	Disposal	Re-use, recovery and recycling potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	MND	MND	MND	MND	MND	MND	MND	MND	MND	X	X	X	X	X

Figure 5.7: Modules covered in the EPD of the indoor roller blind (Epddenmark 2023)

This choice of integrating the EPD data as a processes was made to overcome two main issues:

- EPDs compatibility: OpenLCA allows to import digital EPD. However, these are assessed with corresponding categories to those of EF3.1, the software do not recognise them when making the calculation. Therefore, it is necessary to remodel the data from scratch
- Calculation issues and Monte Carlo simulation: when compatible with the LCIA method, imported EPD results have their own structure in OpenLCA and can be linked manually to the product system to calculate the product's impact. However, this operation must be repeated every time the product system is changed, thus increasing the time demand for such operation and the risk of human error. In addition, OpenLCA ignores the EPD results when performing uncertainty

calculations with Monte Carlo simulation and this leads to incomplete and incorrect results for those calculations.

Production Stage

There are no detailed information about the manufacturing of this specific PSW, besides the description the build-up. The manufacturer Pleotint LCC (U.S.A.) provides data referred to the whole glazing on a brochure (Pleotint 2019), while on the IGDB data referred specifically to the AR laminated pane were found. It was therefore assumed the production of the laminated pane to take place in the company location, specifically in Michigan, regardless of the building site location. The glazing entire production of the glazing is assumed to take place in the USA and its components are assumed to be manufactured in the USA as well. Therefore all the glass panes, both the laminated ones and the internal one, the PVB interlayer, the spacers and the sealant are based on the North American context. The production of the thermochromic material to be applied to the interlayer takes place in the USA as well. The reagents for the production of the AR material are the only that will come from other locations. The static glazing of the benchmark is assumed to be produced in the US as well, with a similar location. The blinds instead are assumed to be manufactured in Western Europe, since this product is widely manufactured in that region as well.

Manufacturing glazing

The manufacturing of laminated glazing with AR interlayer was estimated to be the sum of the corresponding process for static glazing and the required amount of W-doped VO_2 powder. The only difference lies in the interlayer itself: for static glazing, the interlayer consists uniquely of PVB while in the AR interlayer, VO_2 powder is added to the polymeric matrix. PVB layers are commonly produced by melting the resins and extruding the matrix; this is then cooled down progressively through a series of cold rolls and packed as a roll. No information could be found on how the embedding of the powder could affect the process, probably for confidentiality reasons. However, the thickness on the Suntuitive interlayer is assumed to be 1,22 mm (Pleotint 2019); this value is higher than the usual typical 0,38 or 0,76 mm (Vanceva; KBPVB), so an addition of material may need to be considered. The production of the layer itself was also assumed to be the same as in the common PVB production: the addition of VO_2 might impact the energy required by the machine, but this variation is hard to estimate without very specialised knowledge and it s contribution to the overall impact of the product system may easily be negligible.

Installation and removal

Following the LCA practice of other LCAs of windows, these stages were neglected. This is possible since they are supposed to be identical for the two technologies.

Maintenance

For the use stage, only Operational Energy and Replacement were considered. Maintenance of the windows was neglected since identical fr both systems and the maintenance of the blind was neglected since considered negligible by the EPD.

Replacement

The replacement was calculated as the sum of the impacts of the Product stage, construction stage, and End-of-Life. This sum is multiplied by the replacement rate, which is calculated through parameters and updated if changes occur to an ESL when testing some scenarios.

End of life

The End-of-Life stage needs to be modeled carefully: on one hand, it must take into account the impact of VO_2 for the PSW and, on the other hand, it has to be coherent with the Dutch flat-glass recovery chain (Chapter 3). For both systems, the Window is separated from the frame, with the same

assumptions as Owsianiak et al. (2018) and the used frame is treated through the respective waste market. Two scenarios are then considered: Landfill, consisting of the complete landfill of the glazing, and Recycling, consisting of the waste treatment with sorting aimed to; for Recycling scenario, the cullet are cut-off as they exit the sorting process as by-products.
Both options are implemented in the same LCA model and are regulated through a parameter that defines which of the two to choose in both product systems. The glazing treatment was modeled based on the Ecoinvent data and on the data provided by VRN for the year 2022 (Wittekoek 2023). The inputs for the operation at the sorting plant were taken from *Treatment of waste glass pane in burnable frame, sorting plant* and *Treatment of used double glazing, U<1.1W/m2K, laminated safety glass*, from the Swiss context, since it was considered closer to the Dutch one compared to RoW (rest of the world). The mass of aluminium and rubber waste were kept unchanged, while glass waste and byproducts were then adapted with the rate reported in 5.5 and the land-filled glass is treated as inert material. The only difference between the processes of PSW and DWS are the mass of PVB and the emissions of VO_2.

Table 5.5: Flow rates for glass waste used in processes for glass sorting operation, for Recycling scenario

Destination from VRN	Mass (ton)	Modelled flow	flow fraction
Flat glass industry	8284	Glass cullet, high-quality	10%
Insulation products	21361	Glass cullet, low-quality	89%
Packaging industry	50963		
Glass bead industry	667		
Contaminated glass	894	Waste glass (landfill)	1%
Total	82169		

The following diagrams show how the product systems of the PSW (5.9) and the DWS (5.8) were modelled in OpenLCA.

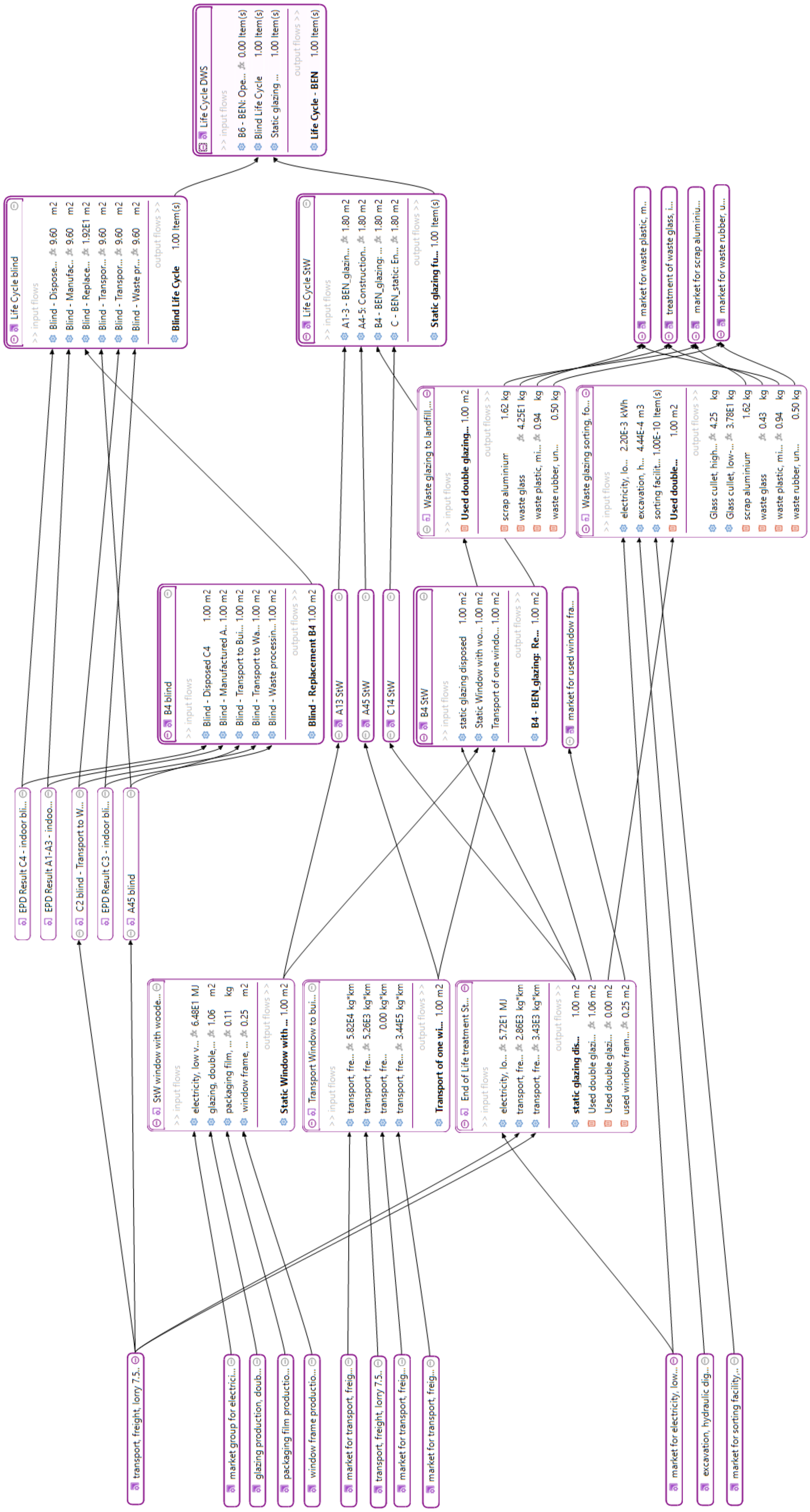


Figure 5.8: Product system of DWS as modeled in OpenLCA

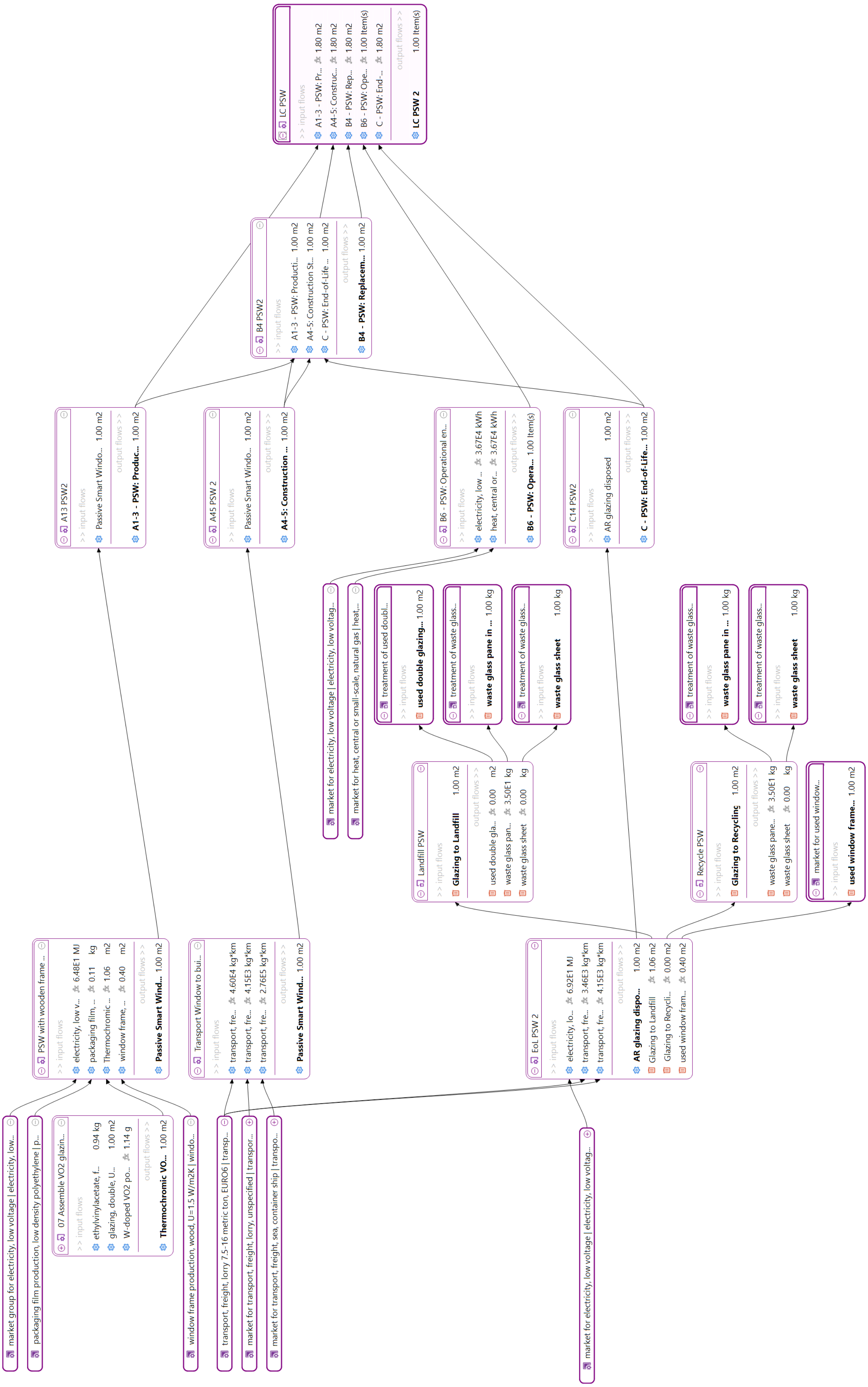


Figure 5.9: Product system of PSW as modeled in OpenLCA

LCA Scenarios

Some sets of scenarios were evaluated for different variables of the product systems. The first set of scenarios is given by combining the ESLs of the PSW and the blind: while the blind can be separated from the static glazing in the DWS and can be replaced independently, the ESL of PSW coincides with that of the AR glazing. For PSW a minimum 12 years was used, based on the considerations of Sirvent et al. (2022), and a maximum of 30 years, from the optimistic, an intermediate baseline value of 20 years was considered too, which, according to the interviews, is the age of the first Suntuitive windows installed currently still functioning. For the blind, a maximum ESL of 45 years, coinciding with the LCA lifespan, and a minimum of 10 years were considered. Two intermediate values were considered too: 15 years as baseline value, taken from the EPD, and 30 years.
Another uncertain parameter is the quantity of AR material in the PSW: 1,14g of W-doped VO_2 powder for 1 m^2 of glazing was taken as baseline value from the assumptions of Sirvent et al. (2022), who used a VO_2 coated PET film. This mass had been estimated as corresponding to a 250 nm thick VO_2 layer from Aburas et al. (2021). However, this last study considered other thicknesses as well, which were used as references to estimate alternative quantities (5.6).Finally, Landfill and Recycling scenarios for the glazing End-of-Life were considered for both product systems, as previously described.

Table 5.6: Mass of VO_2 depending on the layer thickness

Scenario	Thickness (nm) (Aburas et al. 2021)	Used mass of VO_2 (g/m^2 of glazing)
m1	80	0.37
m2	160	0.73
m3 (baseline)	250	1.14
m4	500	2.28
m5	800	3.65

Sensitivity and uncertainty

The uncertainty of the results is calculated only for the baseline scenario, described by these parameters: As first stage for the assessment of the uncertainty, a contribution analysis is done to determine

Table 5.7: Values of the parameters for the Baseline scenarios

Parameter	Value	Description
ESL_PSW	20 ys	Expected Service Life of the PSW
ESL_blind	15 ys	Expected Service Life of the blind of DWS
m_VO2	1.14 g	Mass of VO2 powder in the PSW
EoL_glass	0 (Landfill)	Type of EoL for glass used; 0 = landfill, 1 = sorting and Recycling

the most contributing parameters to the life cycle. These parameters are chosen mainly from foreground processes and are perturbed of the 10% of their value. A parameter is considered sensible if the resulting normalised sensitivity coefficient X_{IS} is higher than 0,5. To calculate the impact of the perturbation, the parameter is modified, the calculation is updated and exported; finally, the parameter is set again to its original value. This is done twice for each parameter (decrease and increment) and repeated individually for each parameter.
The parameters that are selected as sensible for the LCA are then assigned a normal distribution and a Monte Carlo simulation is run for both systems for 10000 iterations.

6

Results and discussion

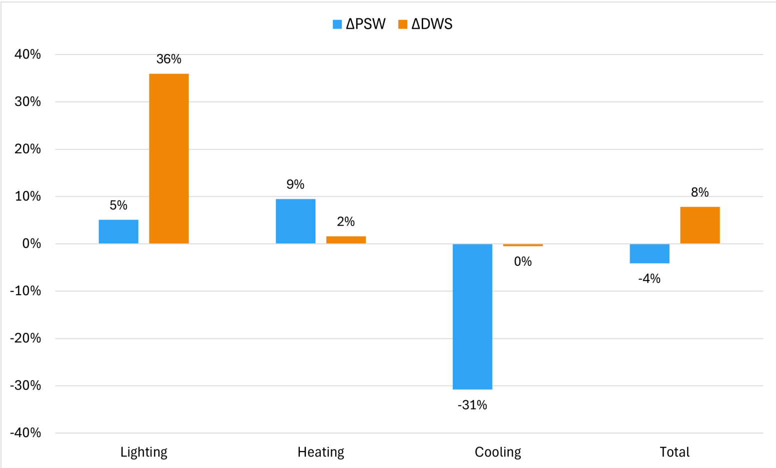
The following chapter consists of the impact assessment and interpretation of the case study, thus reporting and discussing all the obtained results. First, the simulation results are shown; then, the results for the embodied impact are presented and compared and, eventually, the total results with uncertainty are calculated and analysed. The impact categories from EF3.1 are referred to with their abbreviations and, for ease of comprehension, their full names and units are reported in the following table:

Table 6.1: List of all Environmental Impact Categories with respective abbreviations and unit

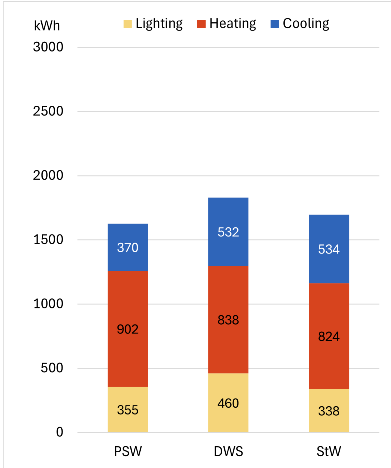
Acronym	Full category name in EF 3.1	Unit
AP	acidification - accumulated exceedance (AE)	mol H+-Eq
GWP	climate change - global warming potential (GWP100)	kg CO2-Eq
ETP	ecotoxicity: freshwater - comparative toxic unit for ecosystems (CTUe)	CTUe
ADPff	energy resources: non-renewable - abiotic depletion potential (ADP): fossil fuels	MJ, net calorific value
EPFW	eutrophication: freshwater - fraction of nutrients reaching freshwater end compartment (P)	kg P-Eq
EPMW	eutrophication: marine - fraction of nutrients reaching marine end compartment (N)	kg N-Eq
EPT	eutrophication: terrestrial - accumulated exceedance (AE)	mol N-Eq
HTPc	human toxicity: carcinogenic - comparative toxic unit for human (CTUh)	CTUh
HTPnc	human toxicity: non-carcinogenic - comparative toxic unit for human (CTUh)	CTUh
IRP	ionising radiation: human health - human exposure efficiency relative to u235	kBq U235-Eq
SQI	land use - soil quality index	dimensionless
ADPmm	material resources: metals/minerals - abiotic depletion potential (ADP): elements (ultimate reserves)	kg Sb-Eq
ODP	ozone depletion - ozone depletion potential (ODP)	kg CFC-11-Eq
PM	particulate matter formation - impact on human health	disease incidence
POCP	photochemical oxidant formation: human health - tropospheric ozone concentration increase	kg NMVOC-Eq
WDP	water use - user deprivation potential (deprivation-weighted water consumption)	m3 world eq. deprived

All the results are reported in the Appendix B.

6.1. Simulation results



(a) Relative difference of the energy demand of PSW and DWS compared to StW



(b) Room energy demand divided per system

Figure 6.1: Results of the energy simulations

For each of the three simulated systems, the estimated annual energy demands for lighting, heating and cooling were obtained (fig:6.1) The relative results were also obtained and displayed in fig. 6.1a. Both PSW and DWS caused an increase in the lighting demand, which was expected: when the thermochromic layer and of the blind activate, they decrease $\tau_{\text{vis}}$of the window system too, thus increasing the need for artificial lighting, which aims to ensure the minimum illuminance level. The large difference between the two technologies can be ascribed to the different mechanisms: the blind (+36%) is either up or down, with no intermediate states, and is modelled on the behaviour of the users, which is also comfort-related and thus not depend only on the energy performance perspective; therefore it may be activated not only when the temperature is too high but also when glare or other sources of nuisance occur, and it may not be deactivated immediately after the nuisance stops. The thermochromic layer instead has several intermediate states, thus reducing τ_{vis}only partially and allowing more visible light than the blind while still reducing the internal gains; moreover, the thermochromic layer reacts exclusively to its temperature, thus neglecting all the parameters related to the users' comfort.
A decrease in the cooling demand was also expected: both dynamic technologies reject solar heat gains, thus reducing the indoor temperature increase and, consequently, the need for cooling. However, the PSW is quite effective in these terms(-31%). In comparison, the savings of DWS are negligible (less than 1%), confirming how indoor blinds are not very effective in reducing solar gains, even though widely applied for this purpose. The increase in heating demand is an expected drawback of these technologies: solar heat gains are beneficial with cold weather and both PSW and DWS may reject some of these too, as it happens for the lighting. The different amount of demand for this system depends again on the efficacy of the technology.
It is finally visible how the PSW causes a small decrease in the energy demand while the DWS increases the total energy demand of the office. This can be ascribed to two main aspects. Firstly, the variation in demand of DWS, gives no savings in cooling while increasing the demand for heating and lighting. Secondly, the relative weight of the different demands: observing the overall results (fig 6.1b), it can be noticed that the demand for cooling is always comparable to the demand for lighting and significantly lower than the demand for heating.
The lower lighting and cooling demands in comparison to heating demand derive from the weather file used: the climate of Amsterdam is mostly cold during winter and does not reach high temperatures in summer, thus usually having low demand for cooling; this effect is increased by the use of official TMY files, based on old data, thus not keeping into account the temperature rise of the last few decades. The proximity of cooling and heating to lighting results, instead, was unexpected and could derive from the modelling of the office itself: the high-performing opaque wall and the minimum air exchange rate, which reflects the properties of new well-insulated buildings, and the five ideal adiabatic surfaces may

have reduced significantly the heat exchange with the outdoor space. However, these assumptions are not considered to significantly affect the final result: very small variations in both the heating and cooling of DWS tell that its effect on the building energy demand can be considered limited, if not counterproductive. The PSW, on the other hand, is confirmed to reduce the overall energy demand: this is similar to the results obtained by Kragt et al. (2022) for Amsterdam but less significant if compared to the study of Aburas et al. (2021) for London.
For the integration of Operational and Embodied impact, the uncertainty was based on the considerations of energy services made by Li et al. (2023) as a relative standard deviation of 15%. The attributional approach chosen was the baseline approach, using as input for the Operational energy use B6 the difference in energy demand between the technology (PSW or DWS) and the baseline window StW (6.2).

Table 6.2: Variation of annual energy demands, used as input for the calculation of the operational impacts of PSW and DWS

	Lighting (kWh)	**Heating** (kWh)	**Cooling** (kWh)	**Total** (kWh)	**σ** (kWh)
PSW	17	78	-164	-69	10,3
DWS	122	14	- 2	133	20,0

The results for the operational energy use impact were calculated the Single Score was calculated through weighting (table B.1).

6.2. Embodied impact results from LCA

Following, the results for the Life cycle assessment of the embodied processes are displayed; these include an analysis of the baseline scenario, alternative scenarios and, finally, an estimation of the uncertainty of the impacts for the baseline scenarios.
Each environmental category has its own unit and its own normalisation and weighting factor,s resulting in a different magnitude of the results. In order to represent together the results for all categories, these are displayed as normalised internally to another system and scenarios. The reference for internal normalisation is usually the baseline scenario for the StW; when a different reference is used, it is reported. The percentages calculated for the contribution of processes or stages are normalised to the StW results as well and, since the impact results for DWS and PSW are usually higher than the reference, the sum of these percentages are usually higher than 100%.

Baseline scenario and initial results

As first step of the results analysis, the the embodied impacts of the baseline scenario were observed: the figure 6.2 compares the embodied impact of PSW, DWS and StW. The impact of PSW is always higher than the DWS, usually with a difference close to 50%; this can be easily explained through the replacement rates: having an assumed ESL of 20 years, the PSW is fully replaced twice during the facade lifespan while the static window of DWS an StW is only replaced once, having an ESL of 30 years. The difference in impact between DWS and PSW vary on each category due to the impact of the blind: this is indeed and additional element to the static window of StW and thus its impact is added to the reference value. The blind has a high impact on HTPnc (+36%) and IRP (+16%), it visibly increases the impact on ADPff, ETP, GWP, and HTPc, but barely affects the other categories (less than 5%). The overall variation in the impact can be visualized through the variation of the Singles Score, which represents a weighted sum of the results of all categories: This increases of 53 % for the PSW, and of 6% for the DWS.

The comparison of these three environmental profiles can already result quite articulated due to the large amount of impact categories considered in the study; however, it is not advisable to always compare only the Single Score, since its value can be considered biased. Rather than analysing all of the categories one by one or just the Single Score, it can be useful to identify the categories with the highest contribution to the Single Score; the figure 6.3 shows how much the result of each category

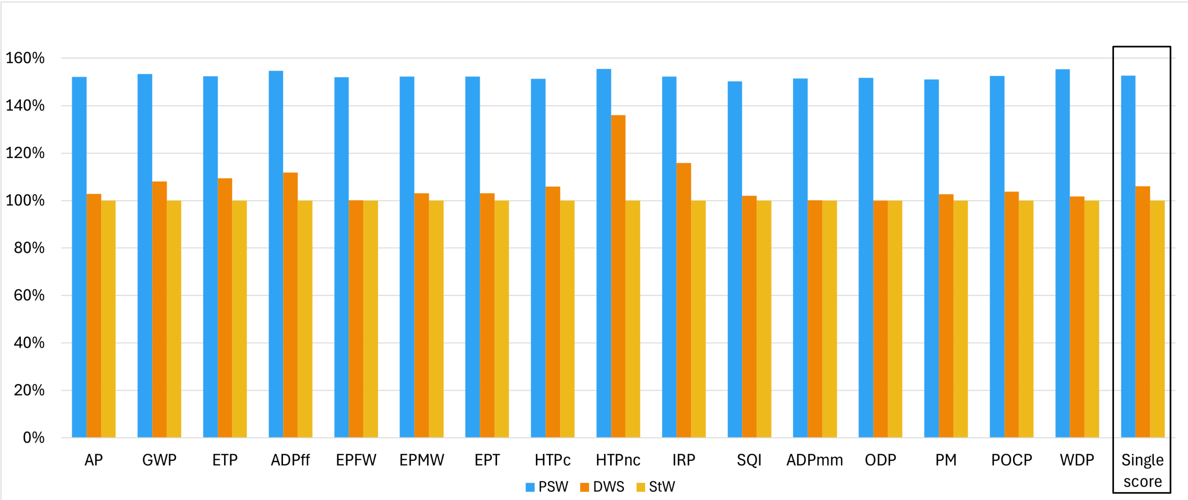


Figure 6.2: Results for the embodied impact for the baseline scenario of PSW, DWS and StW, normalised internally to StW.

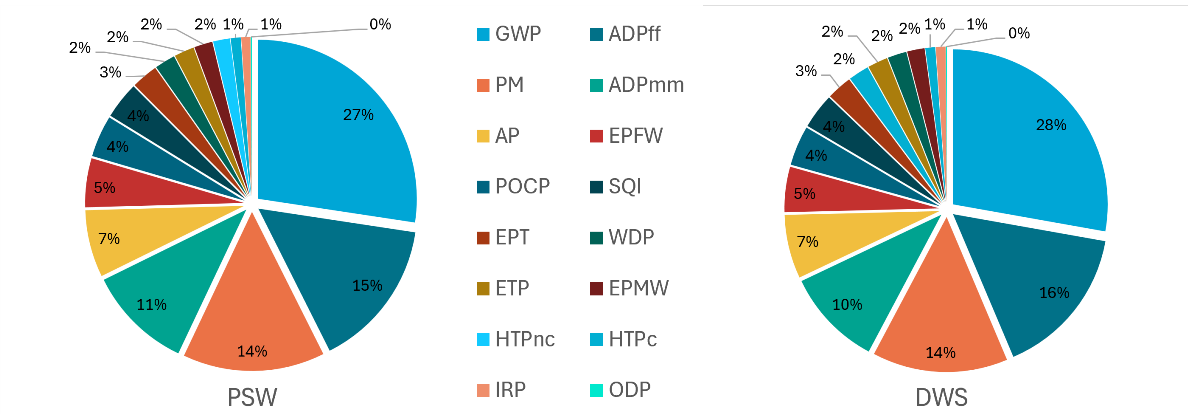


Figure 6.3: Contribution of each category to the Single Score results for the embodied impact of PSW (left) and DWS (right). Most of the impact can be attributed to a few categories: GWP, APDff, PM and ADPmm

contributes to the final result for the Single Score, according to the chosen weighting method. From the figure, it is clear that five categories alone determine around 75% of the overall embodied impact of the product systems: for PSW, GWP is by far the most significant and represents 27,4% of the impact, 15,2% derives from ADPff, 14,5% from PM, 10,7% from ADPmm and 6,8% from AP; the results are very similar for DWS, with variations of maximum 0,6%. The other categories do not register significant variations either; HTPnc varies of only 0,4%. Given that most of the environmental impact can be attributed to five categories, namely GWP, ADPff, PM, APDmm and AP, the interpretation of the results can focus on these categories specifically.

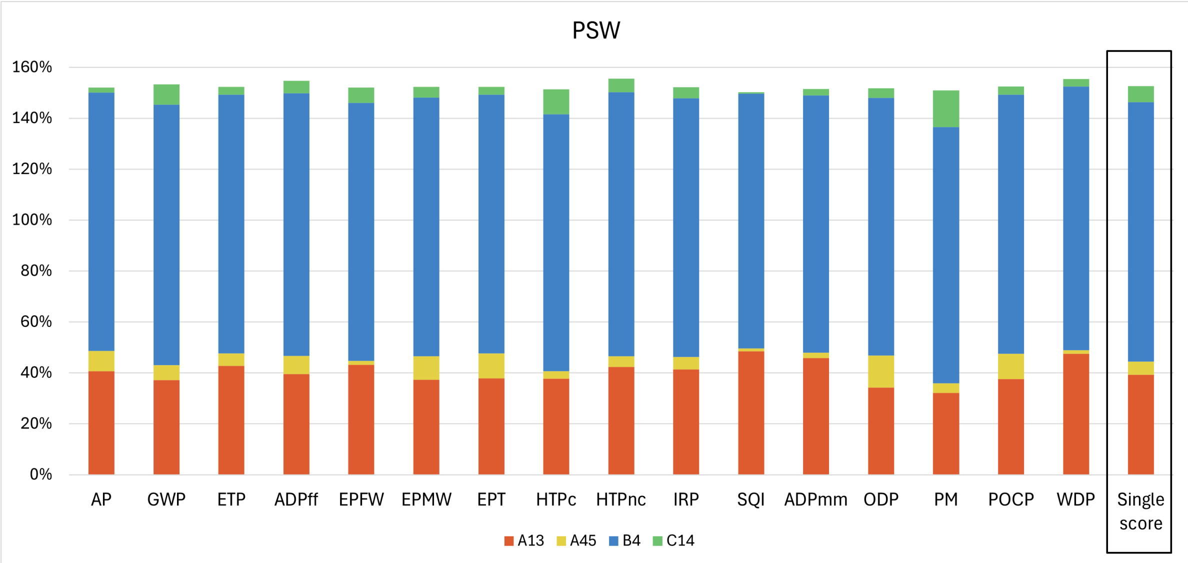
The contribution of the categories to the Single Score also shows the little variation occurring between the two product systems: none of the results varies more than 1 % between the PSW and DWS, showing that most of the impact is likely to derive from the common processes and materials. the contribution of different stages and processes to the embodied impact of PSW and DWS is further analysed in the following paragraphs.

Contribution Analysis

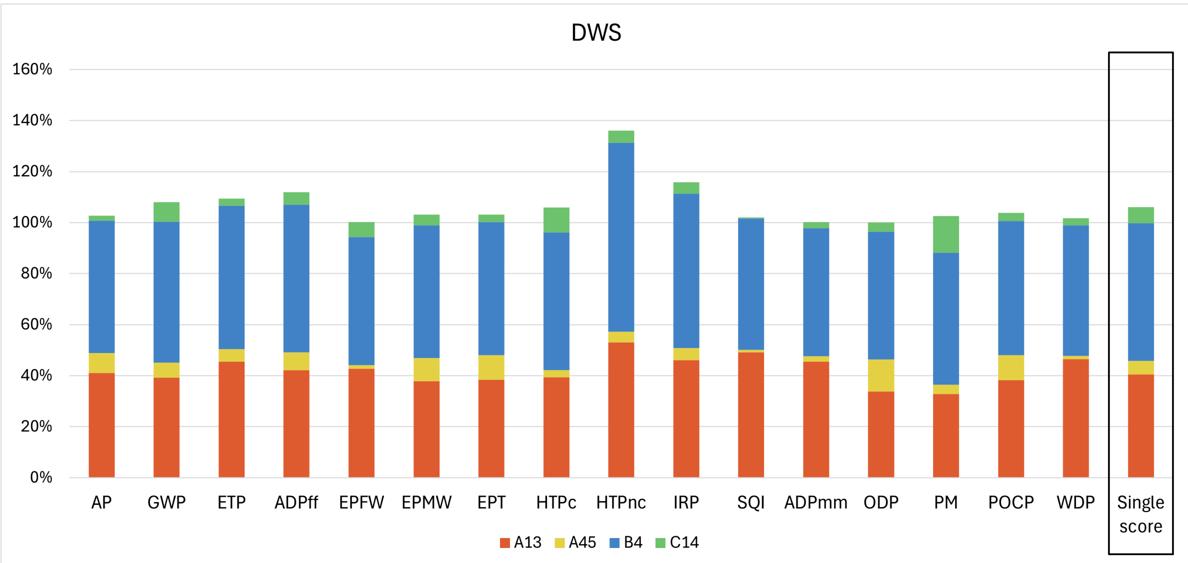
Stages contribution

To identify the most contributing processes to the products' embodied impact, their environmental profile was first observed. The figure 6.4 shows that in all systems the replacement (B4) is always more impactful of all the other stages, because it represents a repetition of all of them. Indeed, B4 is

the 66% of all impacts for PSW and between 50 and 54% for DWS. Since the proportion of the impacts of production, construction and End-of-life are the same within B4, the production stage (A13) is by far the most significant contributor to all the categories' impacts.
In PSW (figure 6.4a), where the percentages of the value are related to the embodied impact of StW, the production stage scores between 32% for PM and 49% for SQI. Observing the main categories, it is noticeable how the End-of-Life (C14) reaches to 8% of GWP and even 14% of PM. The Construction stage (A45) has a higher contribution to EPT and ODP. For the Single Score, 39% derives from A13, and only 5% and 6 % from A45 and C14 respectively.



(a) Stages contribution to the embodied impact results of PSW



(b) Stages contribution to the embodied impact results of DWS

Figure 6.4: Stage contribution to the embodied impacts of PSW and DWS, internally normalised to StW.

Observing the contribution of life cycle stages of DWS (figure 6.4b), it is visible how sensible variations in the results are introduced by the blind. Since DWS consists of a StW with the same ESL and a blind, that share of the impact that exceeds 100% derives necessarily from the life cycle of the blind. This increases the Single Score (6%), some of the main categories, ADPff (12%) and GWP (8%), and most of all HTPnc (36%) and IRP (16%). The Construction and End-of-Life stages have almost identical impacts as for PSW, which could suggest that the impact of these stages is determined mainly by the common processes of the window. The differencesit is also visible though that the Production stage is generally higher for DWS, as it is for the Single Score (41%), GWP (39%), ADPff (42 %) and most of all for HTPnc (53%) and IRP (46%). Even though these two variations are high in relative value within their own category, the chart 6.3 highlighted their shallow effect on the overall result. However, it can be relevant to point out that the increase in non-cancerous human toxicity (HTPnc) from the blind may be due to the polyester and aluminium used in the production of the material, while the low impact of the EoL of the blind across all categories may derive from the modelling in the EPD, which probably assumes high recycling rates.

In general, it is evident how the largest contribution to the impact of each product system derives from the replacement of the product, for DWS and even more significantly for PSW, *thus enhancing the relevance of the Expected Service Life of the products considered in the LCA*. The production stage has by far a higher impact across all the environmental categories, especially for ADPmm, compared to the End-of-Life and Construction stages and it is higher in DWS than in PSW. These results highlight an important contrast: PSW has a higher impact than DWS, especially due to the replacement stage; however, the Replacement stage depends mostly on the production stage, which is generally higher for DWS. This emphasises the role of the Replacement stage and of its different definitions between PSW and DWS in this comparison. to better understand this difference, a process analysis was performed.

Processes contribution

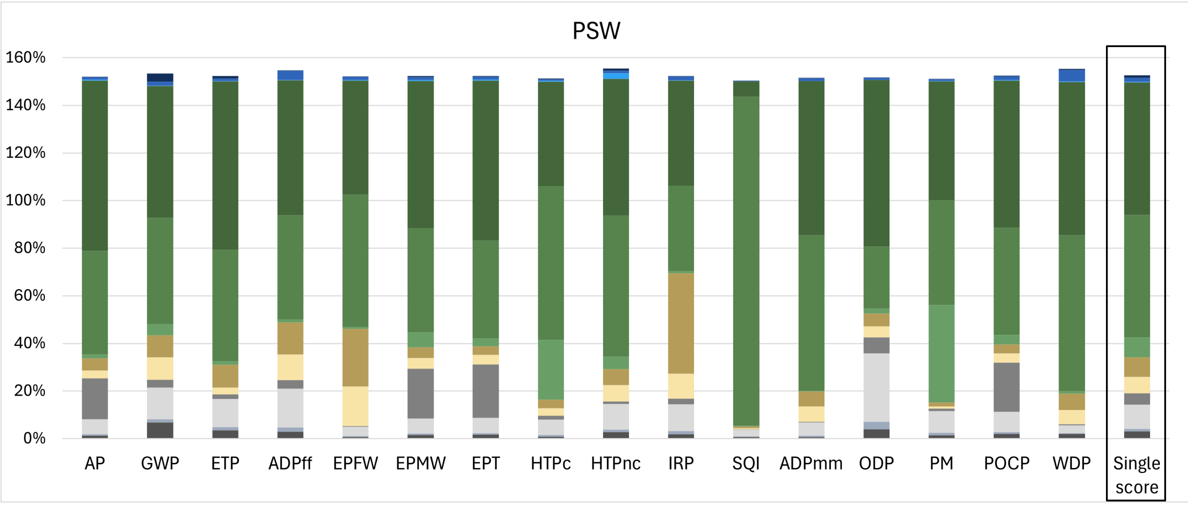
The figures 6.5a and 6.5b show the contribution of single processes to the final result of PSW and DWS: it is clearly visible how the background processes, as expected, contribute by far to most of the impacts in all categories. In both systems, glazing production and frame production and waste treatment are responsible for most of the impact on all indicators, between 42% for IRP and 93% for SQI in the DWS and between 58% and 96% for PSW; glazing and frame indeed represent most of the mass of both products. The manufacturing of the glazing and the frame have comparable impacts in most indicators besides SQI, AP and ODP; the high value for SQI, 89% for the frame production and the high values for PM, 27%, and HTPc, 17%, for its waste treatment may depend on the material chosen for this component, wood. Assuming the use of a different material these results may change proportionally in both PSW and DWS.

The emissions produced by the window transport, especially via ship or lorry during the production stage, are also noticeable in AP, ODP, EPFW, EPT and POCP. Their contribution is similar between the PSW and DWS since both windows are assumed to be produced in the US, where Suntuitive is specifically manufactured, but these impacts could be significantly reduced if the manufacturing and the building location were closer, even better if in the same region.

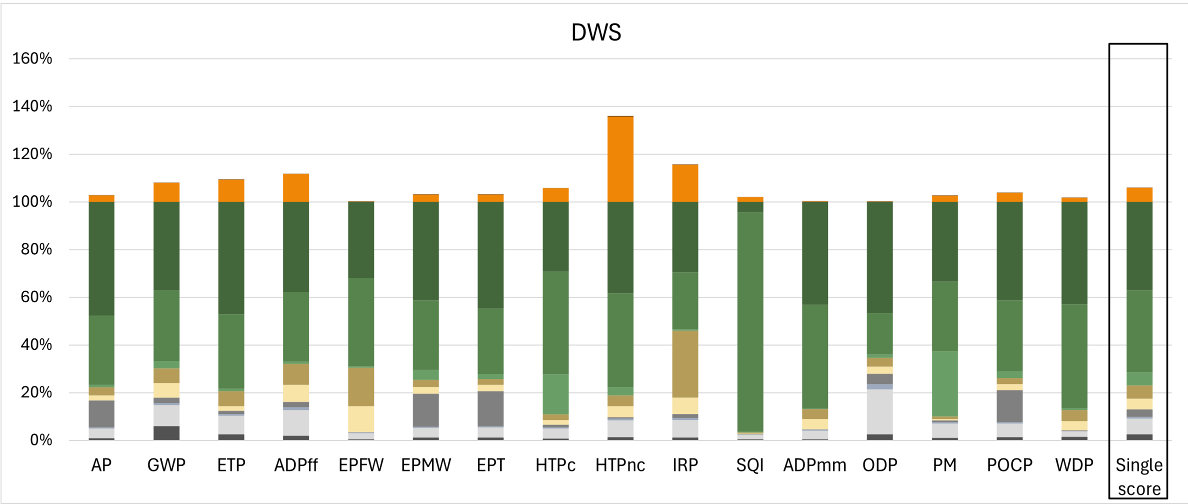
The use of electricity in the assembly of the window and in its waste treatment are relevant too; the input of the first is 10% higher than the second, but the results differ more significantly, especially for IRP, ETP and PM. These variation may derive from the energy sources used by the American and the Dutch electricity mix, since the windows are produced in the US but treated for EoL in the Netherlands. The impact of the American mix is significantly higher in some indicators, as above mentioned, but lower for others, such as EPT and GWP. When considering the same energy input for these processes, the Single Score increases of 8% with the American energy mix: given the biases introduced by the use of a European weighting set and the relatively small variation of the Score, moving the production of the windows to the Netherlands would have overall quite small changes.

Finally, the foreground processes can be analysed. As already noticed, the impact of the blind's production in DWS is evident since it contributes especially to HTPc (36%), to IRP (16%) and to ADPff (12%), but also GWP (7,6%). This results are to be ascribed to the materials used for the fabrication and to the low ESL considered for the blind. However, this process can't be analysed more in detail since impacts of the blind are taken from the EPD thus not allowing to understand more about the blind production. Its End-of-Life and Construction instead have such a low impact that their contribution to the Single Score is lower than 0,5%. On one hand, this reflects the results of the static window, with high impact of the production stage and low for the EoL stage; on the other hand, the EoL impact for the blind could have been underestimated: EPDs are redacted by manufacturers that do not have control on the EoL of their product and might use optimistic assumptions on the impact of these stages.

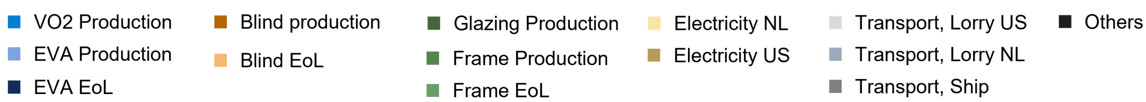
The production and the waste treatment of the additional interlayer material are the most impactful foreground processes for PSW: together, they represent the 2,1% of the Single Score, contributing



(a) Contribution analysis of the embodied impact results of PSW. The foreground processes are shown in shades of blue.



(b) Contribution analysis of the embodied impact results of DWS. The foreground processes are shown in shades of orange.



(c) Legend

Figure 6.5: Embodied impact results of PSW and DWS, internally normalised to StW and showing the contribution of the most contributing processes of the life cycle

to the 4,5% of the GWP impact, especially due to the emissions of the assumed incineration of the material, while the production alone is responsible for the 4% of the ADPff, due to the use of plastic material. These processes are considered foreground because they represent the additional 0,52 kg of interlayer material needed for the PSW, which requires a thicker layer than DWS. The VO_2 powder has a low contribution to the overall impact due to the little mass assumed necessary for the AR layer (only 1,14 g per m^2 of glazing); however, it represents 1,6% of the HTPnc, 1,4% of EPT and 1,3% of EPMW (mostly from the sea shipping during the manufacturing). It does not affect significantly the Single Score since its contribution on categories with high weight is lower.

Contribution to GWP

A useful tool to analyse the results is the Sankey diagram. This visualisation can help in understanding the connection between an impact and the structure of the system, spotting very quickly the most contributing processes and their contributors. Therefore this diagram gives a more insightful visualisation of a specific impact. For example, figure 6.6 exemplifies how the replacement stage (B4 PSW) holds 2/3 of the embodied impact for GWP and how most of it derives from the production of the PSW; this contributes to the Production stage as well, considered separately, and as a result is responsible for the 75% of the whole embodied GWP, mainly due to window frame production and glazing production. It is also interesting to see how most of the GWP for the End of Life treatment (13,8%) derives from the frame's removal (electricity, 6,3%) and disposal (3,1%). Even more interesting, the GWP of landfilling of the glass is 0,1%), so significantly lower than any other shown process, such as plastic disposal. It is interesting to notice that the process *"Waste glazing to landfill"* has a null direct impact, meaning that none of its elementary flow, in this case the vanadium released in the soil, has an impact of GWP.
The diagram for DWS (figure 6.7) shows how most of its GWP derives from the static window component (Life Cycle StW, 92,3%) and that also for DWS most of the GWP impact derives from the production of glazing and frame.
In addition, Sankey diagrams facilitate the comparison of different product systems, showing how different proportions of impacts are distributed within the systems. However, it is less useful in terms of absolute impact: that is reported but the flow is relative to the total impact of their own product systems, not to a single system. The life cycle of the Static window in DWS and PSW share basically the same proportion of GWP among their processes which are identical, except for the production of the VO_2 powder (0,1%) of the additional interlayer material (1,1%) of the PSW.

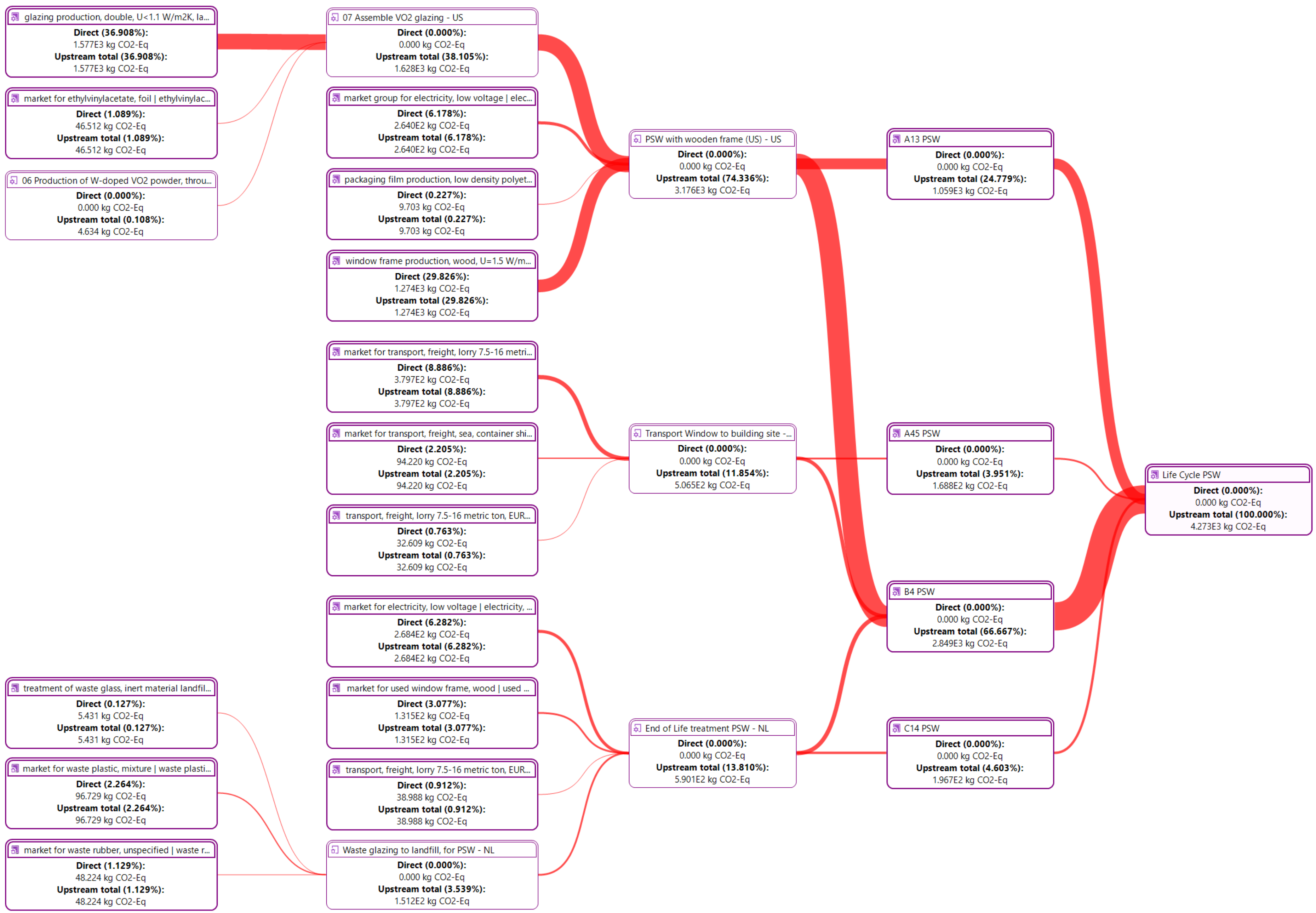


Figure 6.6: Sankey diagram of PSW life cycle, representing the processes' GWP. For ease of representation, only the 25 processes with the highest total upstream GWP are shown.

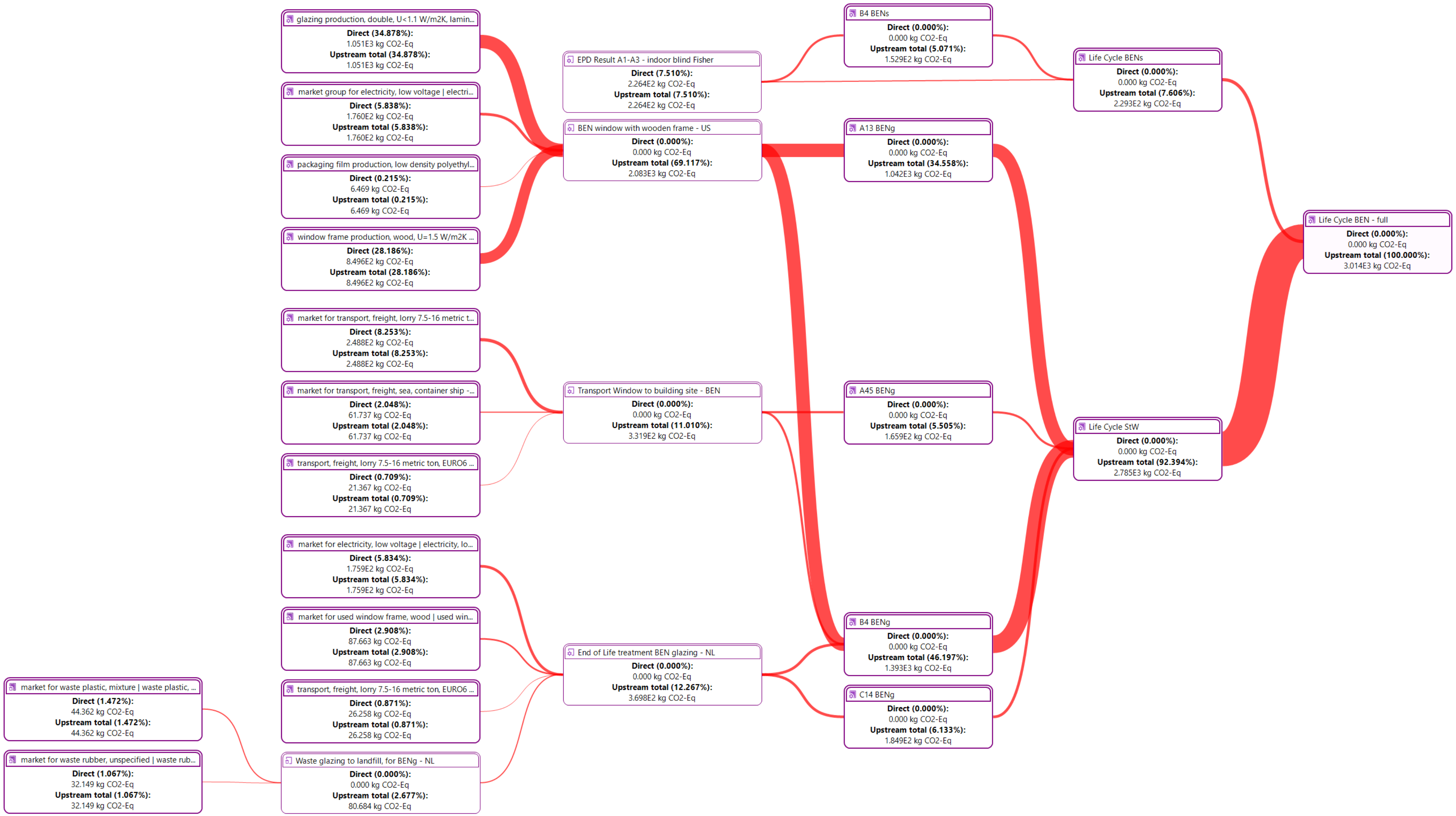


Figure 6.7: Sankey diagram of DWS life cycle, representing the processes' GWP. For ease of representation, only the 25 processes with the highest total upstream GWP are shown.

6.2.1. Results from LCA scenarios

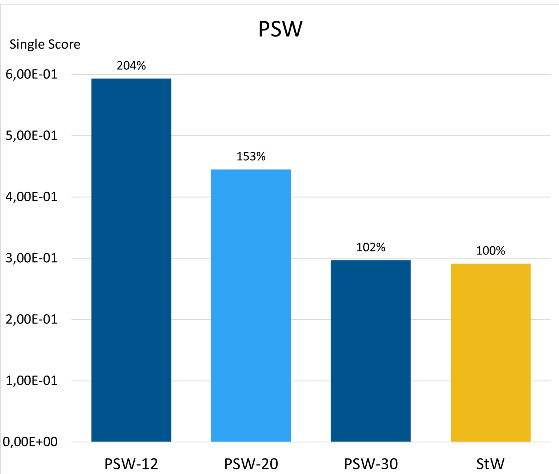
Expected Service Life scenarios

Since both the duration of the PSW and of the sun-shading device were considered uncertain, the combined effect of their Expected Service Life (ESL) variation was analyzed their embodied impacts. Considering a fixed life cycle lifespan of 45 years, the variation of the ESL of a component determines its replacement rate, reported in table 6.3.

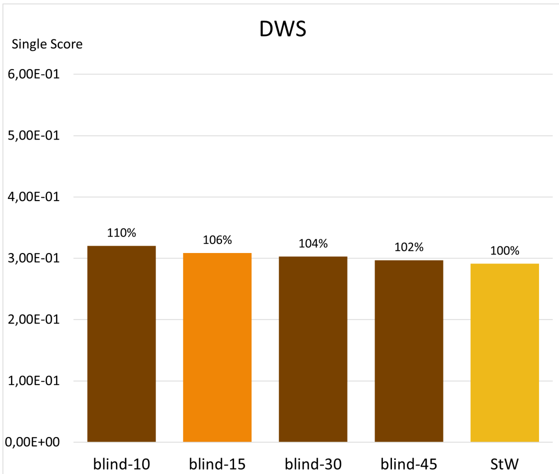
Table 6.3: Expected service Life values used for each technology and corresponding replacement rate used in the corresponding scenario. The values of the baseline scenario of each technology are reported in bold.

	StW	PSW			blind of DWS			
ESL (years)	**30**	12	**20**	30	10	**15**	30	45
Replacements	**1**	3	**2**	1	4	**2**	1	0

In the figure 6.8, the Single Scores of the different ESL scenarios are compared. The two alternative scenarios of PSW (figure 6.8a) show very significant variations of the results: if the service life of PSW is increased and assumed to be the same as the one of StW, PSW-30, their embodied impact give very similar results, with an increase of the Single Score of only 2% due to the AR layer. Instead, if an even shorter ESL is considered, such as PSW-12, the impact increases even further, reaching a Single Score that is more than double of the one by StW (204%). The Single Score of the baseline scenario instead, PSW-20, is the 153% of StW. Considering that also StW is assumed to be replaced once, the most significant share of PSW's impact variation is confirmed to derive from the replacement stage, thus multiplying the impact of Production, Construction and End-of-Life stages. This explains why the baseline scenario, PSW-20, increases the impact of PSW-30 by half its values while the scenario PSW-12 double the impact in comparison to PSW-30. In synthesis, if the whole product system is replaced as a whole, the impacts grow proportionally to the replacement rate and this is equally valid for all the impact categories.



(a) Single Score of PSW in different ESL scenarios. The baseline scenario (20 years) is represented light blue, while the alternative ESL scenarios are represented dark blue

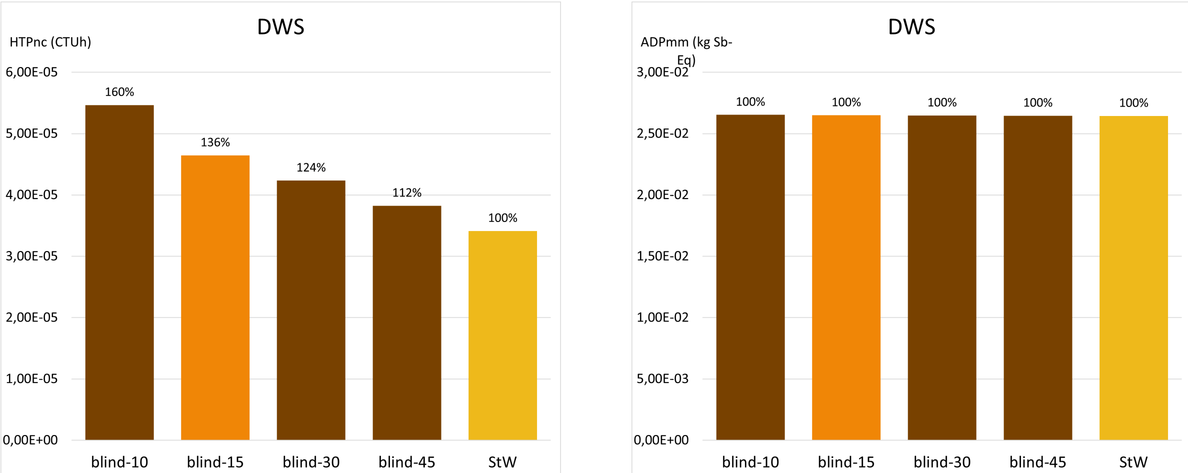


(b) Single Score of DWS in different ESL scenarios of the blind. The baseline scenario (15 years) is represented orange, while the alternative ESL scenarios are represented dark orange.

Figure 6.8: Single Score of DWS and PSW for their ESL scenarios. The StW is shown in yellow in both charts. The label reports the scenarios' impact normalised to StW impact.

The variation of the Single Score of DWS are less significant (figure 6.8b). In the scenario with the highest replacement rate, blind-10, DWS reaches 110% of the STW result, while if the blind is assumed to last for the whole lifespan of the facade, blind-45, it reaches only 102%. The ESL scenarios of DWS thus result in smaller impact variations from PSW. However, this is not a surprising result: the ESL scenarios of DWS indeed define various ESL for the blind, thus for only one of the two components of

DWS, while the ESL of the static window belonging to DWS is unvaried (30 years, as for StW). This means that the ESL scenarios for DWS influence only the replacement rate of the blind, which has a lower impact than the static window, and thus results in less significant variations. As a consequence, the ESL scenarios of DWS do not vary its embodied impact proportionally to the replacement rate but only a portion of it and, thus, this variation can be different across impact categories.



(a) HTPnc of DWS in different ESL scenarios.

(b) APDmm results for DWS in different ESL scenarios.

Figure 6.9: Comparison Embodied impact of DWS for the ESL scenarios, for two impact categories

As the contribution analysis showed, the processes related to the blinds affect more significantly some categories, such as HTPnc, and seem to have negligible effect on others, such as ADPmm. The figure 6.9 shows how these two categories can be differently affected by the ESL of the blinds: the result for HTPnc varies significantly, reaching 160% of the StW result and remarking teh high contribution of the blind to this category. Differently, the result for ADPmm is almost identical in all scenarios.

Overall, it is important to observe that the ESL has a different influence on the embodied impact depending on how the dynamic component of the window, so the AR layer of PSW and the shading device of DWS, are added to it. If the component is integrated, as it is for the VO_2 embedded in the interlayer of the glazing, its failure requires the replacement of the whole building element, causing a higher embodied impact. If instead the dynamic component is separate and can be replaced separately, the total impact will be lower.

VO_2 scenarios

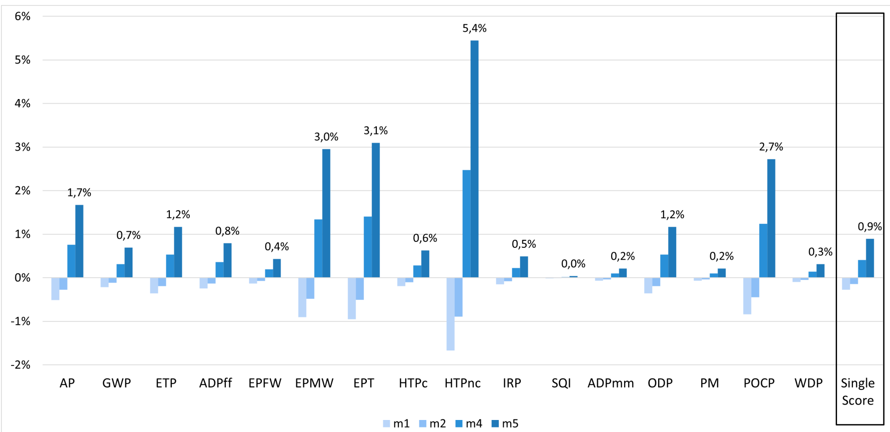


Figure 6.10: Variation of the Embodied impact for VO2 scenarios in relation to the baseline scenario m3= 1,14 g

The mass of VO_2 does not contribute significantly to the overall impact Five scenarios with different quantities of VO_2 were analysed, varying the mass of W-doped VO_2 powder between 0,37 g and 3,65 g. The results in table 6.10 show some variations: HTPnc varies of 5,4%, EPT of 3,1%, EPMW of 3,0%, POCP of 2,7% and AP of 1,7%. Their overall contribution to the Single Score is not significant, with an increase of only 1,2%, but these categories can be analysed to see which foreground processes contribute the most. For the vast majority, these increases derive from the production stage of VO_2, while its End-of-Life has a small impact in comparison. This information must be taken carefully, due to the uncertainty in the modelling of the impact in the End-of-Life of the AR material.
Overall, the mass of VO_2 has a small contribution on the embodied impact, especially when considering the category with the highest weigh in the Single Score.

Glazing End-of-Life scenarios

Two scenarios for the End-of-Life were calculated; the results were observed both the End-of-Life treatment *"Waste glazing"*, corresponding to modules 3 and 4, and for the embodied impact of the life cycle.

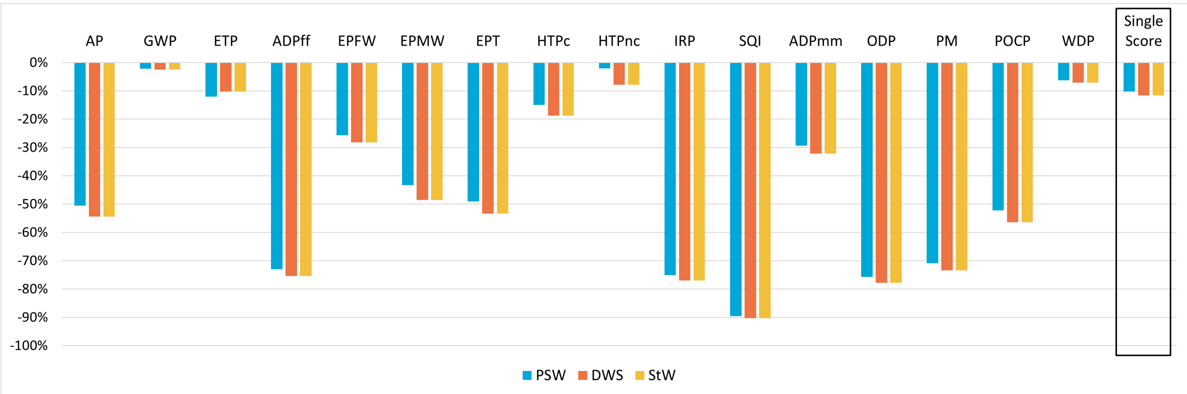


Figure 6.11: Relative embodied impact variation of the *"Waste glazing"* process for recycling scenario, compared to the respective landfill scenario.

Figure 6.11 illustrates that the choice of recycling the glass (*"Waste glazing sorting"*) decreases the impact on every indicator in all products; this is to be ascribed to the modelling of glazing treatment process. While the material quantity is the same and materials such as aluminium, rubber and plastic are treated identically in both scenarios, the recycling scenario crushes the material and only landfills 1% of the mass of glass and the rest of the glass, designated to recycling, has a null impact. Therefore, the impacts determined mostly by the land-filling of the glass decrease significantly, such as SQI , IRP or ADPff, and the other are less affected by this change, such as HTPnc, GWP and WDP. This distinction is meaningful at a process level but, as assessed in the contribution analysis, the contribution of the End-of-Life processes to the total embodied impact of the products is basically negligible. This is confirmed by the low relative impact variations shown in figure 6.12 , where it is clear how none of the indicators decreases of even 1% compared to the landfill scenario. A different modelling of the End-of-life processes, such as the waste treatment of aluminium, rubber and plastic, would certainly cause some changes, but those are expected to have a low magnitude, especially at a system level, also due to the low amount of those materials.

A larger effect could derive from the accounting of the benefits the cullet to be recycled: the use of recycled cullet indeed has a beneficial effect on the manufacturing of new products, which was assessed to be one of the highest contributors to the environmental impact. However, these benefits would concern another product system and accounting for them in this system could lead to double-counting these benefits, thus giving unrealistically optimistic results.
Finally, very similar variations in impacts were observed for all three analysed products, especially for DWS and StW. The EoL of the blinds is not affected by the EoL of the glazing, thus the extreme similarity of the results of DWS and StW was more than expected; the impact of PSW decreases slightly less due

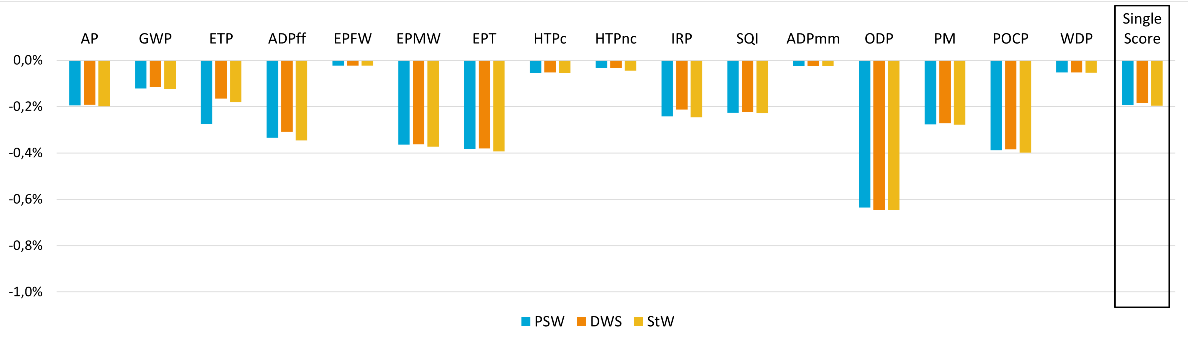


Figure 6.12: Relative embodied impact variation for recycling scenario, compared to the respective landfill scenario.

to the VO_2 emitted in both cases, whose toxicity makes it responsible for 14% and 11 % of Ecotoxicity and for 54% and 64% of human non-cancerogenic toxicity (HTPnc) within the EoL process

6.2.2. Sensitivity Analysis

Table 6.4: Normalised sesitivity coefficient for the embodied impact of PSW and DWS, calculated with a perturbation of 10% of the default value

	PSW					DWS			
	m_layer	t_deliv	EI_Prod	EI_EoL	f_frac	t_deliv	EI_Prod	EI_EoL	f_frac
AP	0,01	0,06	0,05	0,04	0,38	0,17	0,05	0,03	0,38
GWP	0,01	0,04	0,06	0,07	0,39	0,11	0,06	0,03	0,38
ETP	0,01	0,03	0,06	0,02	0,36	0,09	0,06	0,01	0,34
ADPff	0,03	0,05	0,09	0,07	0,37	0,13	0,08	0,04	0,34
EPFW	0,01	0,01	0,16	0,11	0,42	0,03	0,16	0,05	0,43
EPMW	0,01	0,07	0,05	0,05	0,42	0,20	0,05	0,04	0,42
EPT	0,01	0,07	0,05	0,05	0,39	0,21	0,05	0,04	0,39
HTPc	0,00	0,02	0,03	0,02	0,62	0,06	0,02	0,01	0,59
HTPnc	0,01	0,03	0,04	0,05	0,46	0,06	0,03	0,02	0,35
IRP	0,01	0,03	0,28	0,07	0,30	0,09	0,25	0,03	0,27
SQI	0,00	0,01	0,00	0,00	0,93	0,02	0,00	0,00	0,91
ADPmm	0,01	0,01	0,04	0,04	0,46	0,04	0,04	0,02	0,47
ODP	0,01	0,09	0,04	0,04	0,30	0,26	0,04	0,02	0,30
PM	0,00	0,02	0,01	0,01	0,59	0,07	0,01	0,00	0,58
POCP	0,01	0,07	0,05	0,05	0,42	0,21	0,05	0,04	0,41
WDP	0,03	0,01	0,05	0,04	0,45	0,03	0,05	0,02	0,46

Among the processes observed in the contribution analysis, the most impactful are background processes: the most impactful, the glazing fabrication, may be subjected to uncertainty but it is not influenced by parameters belonging to the product systems, while the frame fraction was instead considered relevant. Some foreground processes instead depend on parameters defined in the product system:

- the route's distance for the glazing delivery determines the impact of its transport
- the electricity needed for the frame assembly and separation influences the impact of the electricity consumption both in Europe and in the US
- the mass of the additional layer required for the fabrication of the PSW affects both its production and its EoL
- the quantity of VO_2 powder determines directly its impact

To determine if the related processes have with a significant influence the final result of the LCA, these parameters were perturbed; the table 6.4 shows the normalised sensitivity coefficients resulting from the perturbation in the calculation of the embodied impact.
From these results, it is visible how most of the considered parameters are not sensible enough to impact the embodied impact of the product systems. The only one that resulted sufficiently sensitive is the frame fraction, which is considered in the Monte Carlo calculation.

6.2.3. Uncertainty calculation: Monte Carlo

The uncertainty of the embodied impacts was calculated through Monte Carlo simulation with 10.000 iterations, as suggested by the literature review. Three parameters were assigned with uncertainty, according to the considerations made in the scenarios evaluation and in the sensitivity analysis. These are reported in the table 6.5. The standard deviation was used as uncertainty, since that was used for the Operational impact and the two are to be summed in the next step of the discussion.

The results of the Monte Carlo simulation are shown in the graphs of figure 6.13: PSW has quite

Name	Default value	Uncertainty distribution	σ	Product system
Frame fraction	0,25	normal	0,03	PSW, DWS and StW
ESL_PSW	20 years	normal	2,0	PSW
ESL_blind	25 years	normal	3,0	DWS

Table 6.5: parameters assigned with uncertainty

significant uncertainty, ranging between 17% and 23% of the StW results As could be expected, the results of DWS and StW are very similar: the Single Score differs by only 5% and the uncertainty ranges overlap in most of the categories, especially for those who see a very low contribution of the blinds such as ADPmm and PM. For HTPnc only, the ranges of DWS and PSW overlap. On the other main categories, namely GWP, ADPff and AP, the results of PSW and DWS are quite distant, resembling the baseline results previously discussed. Finally, the relative standard deviation of the Single Score is lower compared to all categories, since it is calculated as the squared root of the quadratic sum of the standard deviations. Due to the smaller uncertainty ranges, the results for the Single Score do not overlap, suggesting that the Embodied environmental impact of PSW is significantly higher than DWS and that StW has less impact than DWS, as expected.

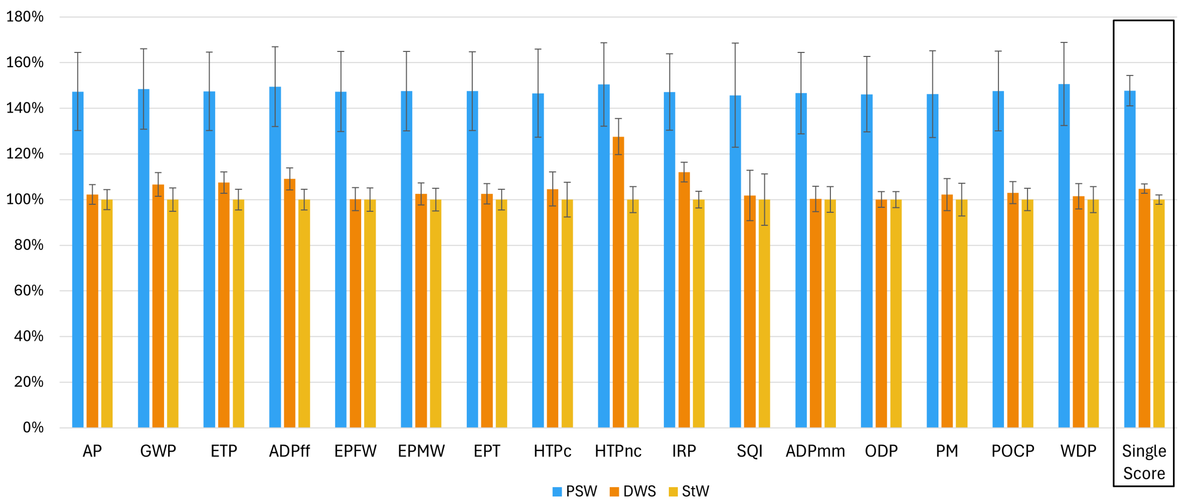


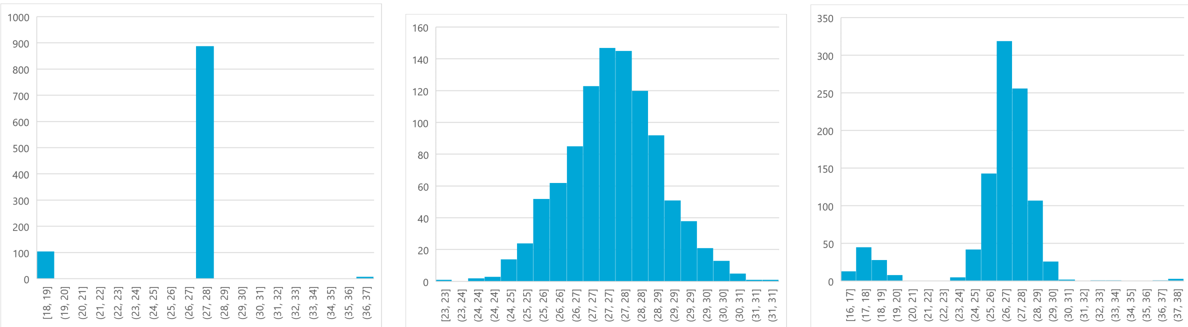
Figure 6.13: Final results for the embodied impact, normalised to StW

These results show that the service life of the products is the most impactful parameter so far analysed since, despite the consideration of uncertainty in the three compared products systems, the PSW has the highest impacts across all categories even when considering uncertainty ranges (exception made for HTPnc).

The effect of the ESL on uncertainty

It is interesting to notice how, for all categories, the uncertainty of DWS and StW are very similar, despite the variation of the lifespan of the blinds; while this is very logical where the blind have a high impact, it is less intuitive for HTPnc and IRP. It can be noticed, instead, how the PSW 's uncertainty

are significantly higher than DWS's in all categories.These discrepancies may be explained through the system modeling and the influence of the ESL.
Firstly, it is useful to focus on the PSW: its ESL varies on a continuous range but its effect on the replacement stage is expressed through the replacement rate, which was defined as a discrete value. Therefore, when the ESL is the only parameter with uncertainty, the impact results assume only three values corresponding to replacement rates of 1, 2 or 3; this is shown in picture 6.14a where only three columns of different size are present. However, in the uncertainty calculation for PSW also entails the uncertainty of the frame fraction: when only this parameter is considered, the life cycle results resemble the normal distribution of the same parameter, as shown in figure 6.14b. Since the replacement of the window implies the replacement of the frame too, the two effects merge: the final results of the life cycle impact gather around three peaks, as shown in picture 6.14c. The uneven value of the peaks is responsible for the high standard deviation of the PSW results.



(a) Probability distribution with ESL_PSW as only variable with uncertainty. The results assume only three values, depending on the replacement rate determined by the ESL.

(b) Probability distribution with frame fraction as only variable with uncertainty. The results five a normal distribution, reflecting the uncertainty distribution of the parameter

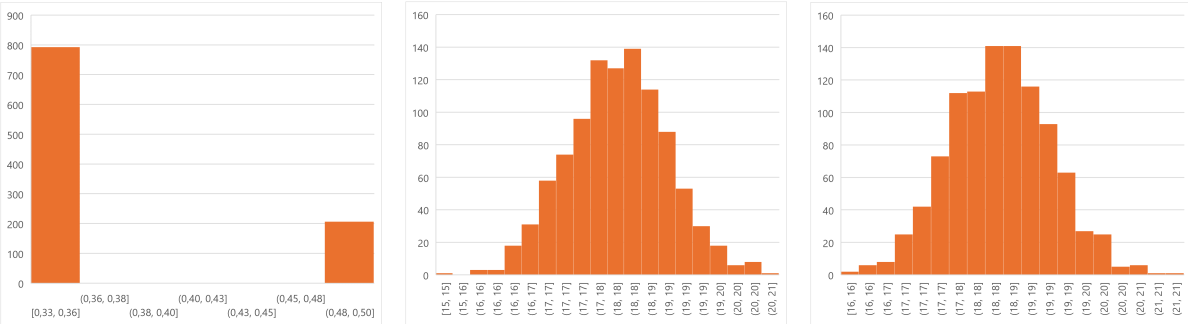
(c) Probability distribution with uncertainty assigned to both ESL and frame fraction. The results are distributed around three peaks, corresponding to the obtained results.

Figure 6.14: Probability distributions of PSW impact for AP with 1000 iterations on Monte Carlo Simulation with different input uncertainties. On the left, ESL_PSW is the only variable with uncertainty. In the centre, the frame fraction is the only variable with uncertainty. On the right, the two effects are displayed together. The x-axis corresponds to a range of results for AP impact and the y-axis to the frequency of that result.

The structure of the LCA model for DWS is different: the two considered variables, ESL_blind and frame fraction, affect separately the two components of the product, StW and the blind, which have two separate and parallel life cycles. ESL_blind is the only uncertain parameter of the blind's life cycle and its results' distribution is discrete due to the approximation made for the replacement rate, as shown in figure 6.15a. The frame fraction instead only affects the static window of the DSW, resulting in a normal distribution, as for figure 6.15b. Since the two life cycle are separated and the StW has significantly higher results compared to the blind, the distribution of DWS is very similar to StW and slightly shifted towards higher values (figure 6.15c). Since the results of StW and DWS have roughly the same distribution, they have a very similar standard deviation.
The discussion about the distribution of the results from the Monte Carlo simulation was illustrated through histograms of the AP results, but the same discussion can be done for all the impact categories considered in this LCA.
The effect of the uncertain parameters on the results' distribution showed that the build-up of the window influences not only its replacement rate, as already known, but also the uncertainty in the results: the life cycle of DWS consists of StW and blind,

6.3. Total impact variation

As final step of the LCA interpretation, the total impacts were calculated for PSW, DWS and StW as the sum of operational and embodied impacts. Then, for PSW and DWS the impact variations for the StW result were calculated (figure 6.16). As expected, DWS always increase the environmental impact of StW, due to its increase of the energy demand and, consequently, of the operational impact.



(a) Probability distribution of the blind's life cycle, with ESL_blind as only variable with uncertainty. The results assume only two values, depending on the replacement rate determined by the ESL.

(b) Probability distribution of the StW's life cycle, with frame fraction as only variable with uncertainty. The results are distributed around three peaks, corresponding to the results obtained

(c) Probability distribution of DWS's life cycle, with the summed effect of ESl_blind and frame fraction uncertainties. The results' distribution is very similar to StW's.

Figure 6.15: Probability distributions of AP impact with 1000 iterations on Monte Carlo Simulation, considering different components. On the left, the blind's life cycle, where ESL_blind is the only variable with uncertainty. In the center, the StW's life cycle, where the frame fraction is the only variable with uncertainty. On the right, the DWS 's life cycle, where both parameters vary. The x-axis correspond to a range of results for AP impact and the y-axis to the frequency of that result.

For PSW instead, the Operational impact was lower than StW's, giving a decrease of the operational impact.

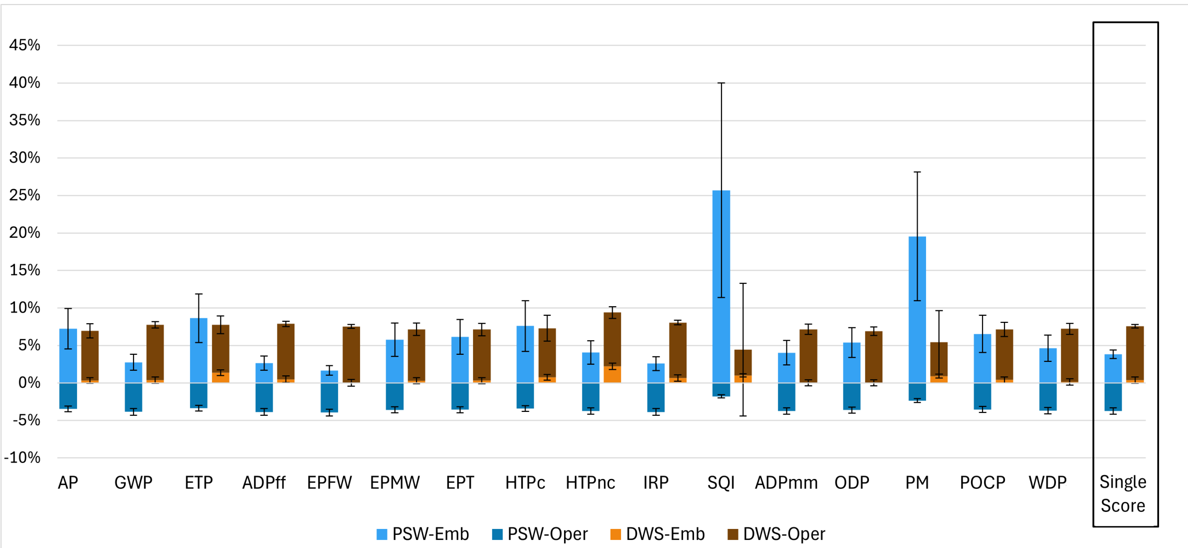


Figure 6.16: Embodied and Operational impact variation of PSW and DWS relative to StW total impact, with respective standard deviation.

The sum of relative impact variations of PSW and DWS (ΔPSW and ΔDWS) were finally calculated (table 6.6) and shown in the figure 6.17. As said, ΔDWS is always positive, while PSW has a less uniform result. In most categories, including the majority of the main ones and the Single Score, ΔPSW is lower than ΔDWS thanks to the saving of energy demand in the Opeartional stage; this means that using the Passive Smart Window has a lower total impact than using the Dynamic Window System. ΔPSW is less ΔDWS of 7,5% for the Single Score, of 8,8% for GWP, of 9,1% for ADPff and of 6,8% on ADPmm. In some categories, even though ΔPSW is lower than ΔDWS, the uncertainty ranges overlap, as it happens for AP.
On two categories, namely SQI and PM, ΔDWS is lower than ΔPSW, with high differences but also high uncertainties: the higher impact of the PSW can be attributed to the higher weight of the background processes in these categories, as highlighted in the contribution analysis, combined with the higher replacement rate of the PSW. However, for both categories the uncertainty ranges overlap, meaning

that the two variable could assume the same value.

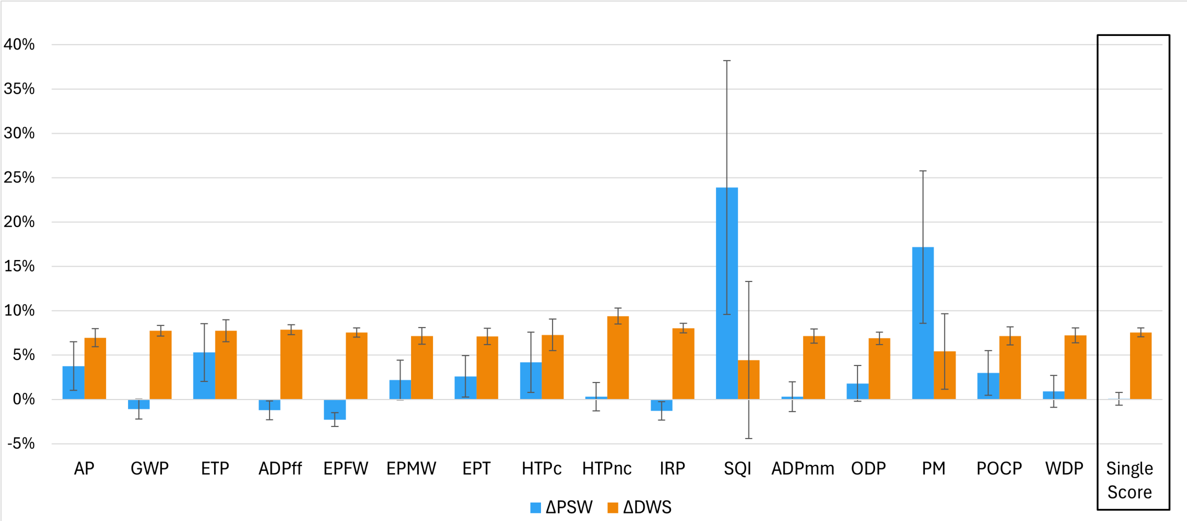


Figure 6.17: Total impact variation of PSW and DWS relative to StW total impact (△PSW and △DWS), with respective standard deviation.

Table 6.6: Total impact variation of PSW and DWS compared to the total impact of StW.

		AP	GWP	ETP	ADPff	EPFW	EPMW	EPT	HTPc	HTPnc	IRP	SQI	ADPmm	ODP	PM	POCP	WDP	Single Score
PSW	value	3,8%	-1,1%	5,3%	-1,2%	-2,3%	2,2%	2,6%	4,2%	0,3%	-1,3%	23,9%	0,3%	1,8%	17,2%	3,0%	0,9%	0,1%
	σ	2,7%	1,1%	3,3%	1,1%	0,8%	2,2%	2,3%	3,4%	1,6%	1,0%	14,3%	1,7%	2,0%	8,6%	2,5%	1,8%	0,7%
DWS	value	7,0%	7,7%	7,7%	7,9%	7,5%	7,2%	7,1%	7,3%	9,4%	8,0%	4,4%	7,2%	6,9%	5,4%	7,2%	7,2%	7,6%
	σ	1,0%	0,6%	1,2%	0,6%	0,5%	0,9%	0,9%	1,8%	0,9%	0,5%	8,9%	0,8%	0,7%	4,3%	1,0%	0,8%	0,5%

It is important to point out one aspect of these results: most of the impact variations, even when considering the uncertainty, are positive, meaning that the impact of the dynamic technology is higher than a common static window, even considering the energy demand of the building. This result highlights that the solar gains control is insufficient to produce an improvement of the environmental impact, meaning that the decrease of operational impact of PSW and DWS from StW was not sufficient to compensate for the increase of embodied impact.

This result however is not definitive: based on the previous discussion, it is reasonable to consider that the operational impact was underestimated due to the definition of overly conservative boundary conditions for the energy simulation. This was made relying on the expectation of a very high contribution of the operational stage on the overall impact and has probably led to an excessively pessimistic scenario. The following assumptions could be varied to produce more realistic results concerning mostly the energy model:

- the envelope definition: the very high performance of the facade seems to produce excessively low results in terms of heating and especially cooling, compared to other studies for the energy performance of PSWs. This causes the dynamic solutions PSW and DWS to have very reduced beneficial, or even pejorative, effect on the energy demand. A facade with a lower thermal resistance would decrease this discrepancy. In addition, different modelling of the space may lead to more realistic results as well: the five adiabatic surfaces of the room may be part of the source of the low energy dispersion and gains and assigning these surfaces with a realistic thermal resistance would for sure increase the energy demand of the space
- the chosen energy output: the generic definition of the building, led to the assumption of an ideal heating and cooling system, thus using the energy demand as input for the Operational impact of the LCA. Even though the same was done for the electricity needed for the lighting, it is possible to assume that the energy dissipation of heating and cooling systems is significantly higher than

the lighting system; this may have led to the use of dis-proportioned energy outputs, causing the unbalanced results discussed above.

- the climate: the energy saving induced by solar gain control technologies act on mitigation of overheating, thus reducing the building's cooling demand. Even though PSWs can reduce the energy demand in colder climates as well, as for the climate of the Netherlands, they are more effective in hotter climates where it is used to reduce cooling demand. Moreover, the use of current climate files, based on data that do not consider the increase of temperature of the last decades, may have additionally underestimated the cooling need. Even though the choice made is legitimate and coherent with the rest of the life cycle assumptions, it may have concurred to the underestimation of the the energy demand for the building conditioning.
- the blind modelling: the increased energy demand of DWS may derive from a wrong combination of blind properties and activation. Theoretically, the choice of any blind is legitimate but it may not be coherent with the algorithm used for the occupants' interaction with the blind itself: if the blind is too dark compared to the one the algorithm is developed for, his may be activated when it is not necessary, thus possibly rejecting useful solar gain and increasing the need for heating; similarly, it may decrease the daylight when not actually needed, thus rising the lighting demand

		PSW						DWS					
Category	**Reference unit**	**ΔEmb**	**σ**	**ΔOper**	**σ**	**ΔTotal**	**σ**	**ΔEmb**	**σ**	**ΔOper**	**σ**	**ΔTotal**	**σ**
AP	mol H+-Eq	8,47E+00	3,17E+00	-4,05E+00	6,07E-01	4,42E+00	3,22E+00	3,95E-01	1,11E+00	7,75E+00	1,16E+00	8,15E+00	1,60E+00
GWP	kg CO2-Eq	1,29E+03	4,89E+02	-1,80E+03	2,70E+02	-5,06E+02	5,59E+02	1,77E+02	1,93E+02	3,44E+03	5,16E+02	3,62E+03	5,51E+02
ETP	CTUe	8,17E+03	3,06E+03	-3,16E+03	4,74E+02	5,02E+03	3,10E+03	1,29E+03	1,11E+03	6,04E+03	9,07E+02	7,33E+03	1,43E+03
ADPff	MJ, net calorific value	1,69E+04	6,16E+03	-2,47E+04	3,70E+03	-7,77E+03	7,19E+03	3,12E+03	2,26E+03	4,73E+04	7,09E+03	5,04E+04	7,44E+03
EPFW	kg P-Eq	3,96E-01	1,53E-01	-9,34E-01	1,40E-01	-5,38E-01	2,08E-01	1,89E-03	6,01E-02	1,79E+00	2,68E-01	1,79E+00	2,75E-01
EPMW	kg N-Eq	1,70E+00	6,51E-01	-1,06E+00	1,59E-01	6,45E-01	6,70E-01	8,89E-02	2,48E-01	2,03E+00	3,04E-01	2,12E+00	3,93E-01
EPT	mol N-Eq	1,78E+01	6,66E+00	-1,02E+01	1,54E+00	7,52E+00	6,83E+00	9,43E-01	2,37E+00	1,96E+01	2,94E+00	2,06E+01	3,78E+00
HTPc	CTUh	1,14E-06	5,08E-07	-5,13E-07	7,69E-08	6,28E-07	5,14E-07	1,14E-07	2,60E-07	9,82E-07	1,47E-07	1,10E-06	2,99E-07
HTPnc	CTUh	1,73E-05	6,55E-06	-1,59E-05	2,39E-06	1,32E-06	6,97E-06	9,43E-06	3,34E-06	3,05E-05	4,58E-06	3,99E-05	5,66E-06
IRP	kBq U235-Eq	1,08E+02	3,93E+01	-1,62E+02	2,42E+01	-5,33E+01	4,62E+01	2,77E+01	1,30E+01	3,09E+02	4,64E+01	3,37E+02	4,82E+01
SQI	dimensionless	5,24E+04	2,92E+04	-3,65E+03	5,47E+02	4,88E+04	2,92E+04	2,07E+03	1,81E+04	6,98E+03	1,05E+03	9,05E+03	1,81E+04
ADPmm	kg Sb-Eq	1,23E-02	4,95E-03	-1,14E-02	1,71E-03	9,71E-04	5,24E-03	7,33E-05	2,09E-03	2,18E-02	3,27E-03	2,19E-02	3,88E-03
ODP	kg CFC-11-Eq	1,29E-04	4,72E-05	-8,59E-05	1,29E-05	4,30E-05	4,89E-05	2,82E-07	1,36E-05	1,64E-04	2,47E-05	1,65E-04	2,82E-05
PM	disease incidence	1,31E-04	5,74E-05	-1,57E-05	2,36E-06	1,15E-04	5,74E-05	6,12E-06	2,84E-05	3,01E-05	4,52E-06	3,63E-05	2,88E-05
POCP	kg NMVOC-Eq	5,03E+00	1,91E+00	-2,71E+00	4,06E-01	2,32E+00	1,96E+00	3,20E-01	7,26E-01	5,19E+00	7,78E-01	5,51E+00	1,06E+00
WDP	m3 world eq. deprived	4,07E+02	1,54E+02	-3,25E+02	4,88E+01	8,17E+01	1,61E+02	1,16E+01	6,40E+01	6,23E+02	9,34E+01	6,34E+02	1,13E+02
Single Score	-	1,37E-01	1,99E-02	-1,34E-01	2,01E-02	2,65E-03	2,83E-02	1,37E-02	8,32E-03	2,57E-01	3,85E-02	2,70E-01	3,94E-02

Table 6.7: Embodied, Operational and Total Impact variation for PSW and DWS, with the respective standard deviations the results were summed and weighted. The contribution of the operational energy to the total is shown as well.

7 Conclusions and Recommendations

7.1. Conclusions

This study aimed to develop a framework for the assessment of the environmental impact of Passive Smart Windows (PSW) through the LCA approach, considering both operational and embodied impact. The framework was initially defined through literature research and interviews with experts in the sector of transparent facade technologies. This was then applied to a case study, where a thermochromic window was assessed with the EF 3.1 LCIA method and compared to a dynamic window system DWS, composed of a Static Window and an indoor blind. The final total results of the two technologies were calculated as impact differences relative to a benchmarking static window StW.

PSW total impact variation resulted lower than DWS for most impact categories, but scored positively for several of them, indicating a higher impact in comparison with StW. This result is due to the operational impact, which was less significant than what the literature suggested because of several factors: the high performance of the building envelope coupled with a wide temperature set-point range, resulted in a notable increase in lighting demand relative to heating and cooling demands. As a result, the balance between the benefits and drawbacks associated with the use of PSW within the operational impact was different from the expectations. In addition, the choice of energy demand as output of the simulation, deemed overly conservative, diminished the significance of the operational impact within the total impact and exacerbated the comparison between PSW and StW. A less insulating building envelope, a narrower set-point range and the choice of energy consumption as operational energy would increase the relevance of the operational impact, decreasing the PSW total impact variation.

Contrary to the initial expectation of this study, it is not possible to exclude the context of application of the environmental assessment from it. The reduced availability of data on the foreground processes, such as the production of VO_2 or the End-of-life of the glazing, and the nature of the LCA itself required several assumptions on the process to avoid an excessive level of uncertainty. For the embodied impact, it was necessary to assume a geographical context for the estimation of transports and the choice of process data, while, for the operational impact, the context played a pivotal role in determining weather conditions, building properties and services.

The Expected Service Life of the AR layer and its method of integration in the glazing build-up were identified as the most relevant factors of PSW's embodied impact. The processes' contribution showed that the Production stage represented the largest share in all of the impact categories for both PSW and DWS. Specifically, the static glazing and the frame contributed to 71% of the Single Score for the PSW and to 67% for DWS, while all the processes in common with a static window StW account for 98% of PSW's Single Score and 94% of DWS'. The embodied impact of PSW increased by nearly 50% in all categories due to the reduced Expected Service Life of the technology: this shows how the impact of using the Auto-Responsive material (AR) in a window is low per se, but it has a sensitive impact if it affects the ESL of the whole PSW, thus increasing replacement rate. For the DWS instead, the separation of the two components maintains a distinction between the replacement of the blind and the window, thus producing a lower increase in the embodied impact of DWS. The contribution of the AR to the embodied impact may change depending on the specific material, but the most relevant factors for the embodied impact of a PSW are its durability and its build-up: if the AR layer is included within the glazing, a lower impact is ensured if the PSW can last as long as the corresponding StW. If the AR layer is an adhesive film, a more frequent replacement is needed but with lower impact, since the layer and the static window could be decoupled.

Blinds were assessed not to be a suitable term of comparison for PSW in terms of solar gains control. DWS scored positive variation for all total impacts in the case study, due to the lack of energy demand savings in comparison to StW. This demand increase is ascribed to the blinds as shading devices, which cannot properly prevent the solar gains, and to modelling of their activation by the users, who may be driven also by different factors from the indoor temperature such as glare and comfort. This suggests the need for comparison with different types of widespread sun-shading devices.

Even though its impact was negligible in the case study results, the inclusion of AR material is very hard to determine without the direct involvement of producers and experts. The research of information and environmental data for PSWs and windows in general, was complicated by two main aspects. The novelty and confidentiality of AR technologies limit the completeness of information on the used materials and on their production, while the rarity of these materials makes them not easily available on LCA databases and difficult to estimate; as a consequence, it is necessary to rely on few specific sources, increasing the uncertainty of the calculation. Strong assumptions were adopted for the production method of the AR material and even more for End-of-life processes; these appear to be mostly uninvestigated, for AR material especially but also for the flat glass industry in general. The End-of-Life treatment of flat glass was investigated through interviews, understanding that in most regions it consists just of landfill, while in some, such as the Netherlands and France a more complex recovery system is being developed. However, the results of the case study showed that the variation of the End-of-Life scenario has a negligible effect on the embodied impact.

The Single Score helped in simplifying the results analysis, also by highlighting few impact categories that could be considered more relevant than the others. The decision to utilize a specific weighting set certainly entails inherent biases and necessitates thorough consideration. However, if the prevalent variation in the embodied impact is ascribed to the ESL, the Single Score can be regarded as a valid indicator: as long as the ESL determines the replacement of the whole product, it modifies proportionally the impacts in all categories and so the Single Score, whose variation is then representative for the variation of all the considered categories.

Finally, the assessment of the operational impact is partial since it focuses solely on the energetic performance of PSWs and DWS, overlooking other aspects such as glare, user comfort and time adaptability of the technology. These factors are influenced differently by PSW and blinds and have repercussions on the applicability of the technology, due to its consequences of comfort, and on the operational energy, by the inclusion of blinds, but were disregarded. This omission highlights two shortcomings of the current assessment: PSWs could address glare inadequately, necessitating additional blinds or potentially rendering them unsuitable for future projects. The lack of control of the facade from the users may lead to thermal discomfort and consequent action on the cooling and heating system, thus modifying the operational energy. In addition, in the context of climate change, the selected AR material might not effectively manage solar gains as expected and, if integrated into the glazing, replacement becomes difficult, compromising energy savings or necessitating more frequent replacement, with a higher total environmental impact. Understanding these aspects is crucial for evaluating the effectiveness of deploying these technologies in the future.

7.2. Recommendations

The conclusions drawn from the study underscore a few limitations inherent in the developed framework, both in its application and in its formulation. Regarding the application of the framework, the following recommendations are proposed:

- Data availability for PSW production was identified as a significant challenge, with existing knowledge often inaccessible. Collaboration with PSW producers is essential to obtain primary data and detailed information about the production process. This collaboration can facilitate a more accurate estimation of the production stage impact, improving the reliability of LCA results. Furthermore, the estimation of the End-of-Life stage impacts of Ar materials may necessitate input from experts, particularly in chemistry and environmental impact assessment fields.
- It is advised to avoid the evaluation of PSW in isolation and instead contextualize its assessment within a defined project framework. By incorporating specific building envelope properties and data on building systems, especially for cooling and heating, energy simulation results would gain precision. This reduction in assumptions and uncertainty would enhance the results. Additionally, contextualizing PSW within a building project would allow to consider all windows on the facade as functional unit, avoiding unrealistic effects on energy use caused by adiabatic surfaces.

Furthermore, additional research is warranted to enhance the framework itself:

- A comprehensive investigation into the Service Life of PSW is suggested, with a focus on real-world applications to furnish impartial and up-to-date data. This study should entail the durability of PSWs and the factors influencing their efficacy over time, including potential causes of degradation. Additionally, it should delineate the implications determined by the three different integration options of the Auto Responsive layer in the glazing of the PSW.
- The comparison should be extended to different types of sun-shading devices for the Dynamic Window System. The shading device should be chosen given its solar gains control properties; when automatised and active devices are considered, such as possible Electrochromic windows, the difference between their active and passive functionality should be considered and properly addressed.
- Exploring alternative weighting sets for interpreting LCA results is recommended. This exploration would aim to determine whether the relevance of foreground processes of PSW increases or if replacement rate and ESL remain the most significant factors in the determination of the embodied impact.
- Finally, the adoption of a multi-criteria assessment is recommended to comprehensively evaluate the performance of Passive Smart Windows. This approach should consider factors such as glare, users' thermal comfort and the long-term adaptability of PSW technology. In designing this assessment, several critical issues must be addressed. First, the effect of the absence of active user control on thermal and visual comfort levels. Second, the effect of possible modifications in climate conditions over a 20-30 years lifespan on the efficacy of PSW in maintaining indoor comfort, since the technology lacks tuning capabilities. Third, the definition of an approach suitable to incorporate comfort evaluation and the long-term with the developed framework, thus with the environmental impact assessment. Addressing these questions will enhance the robustness and applicability of the assessment methodology, providing a wider and more complete comparison of PSW with alternative glazing technologies.

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A

Appendix - Case Study input data

A.1. Normalisation and Weighting

Table A.1: Normalisation factors for 3.1 used in the LCA, taken from Andreasi Bassi et al. (2023)

Acronym	Impact Category	Unit	NF 3.1
AP	Acidification	mol H+ eq./person	5.56E+01
GWP	Climate change	kg CO2 eq./person	7.55E+03
ETP	Ecotoxicity, freshwater	CTUe/person	5.67E+04
ADPff	Eutrophication, freshwater	kg P eq./person	1.61E+00
EPFW	Eutrophication, marine	kg N eq./person	1.95E+01
EPMW	Eutrophication, terrestrial	mol N eq./person	1.77E+02
EPT	Human toxicity, cancer	CTUh/person	1.73E-05
HTPc	Human toxicity, non-cancer	CTUh/person	1.29E-04
HTPnc	Ionising radiation, human health	kBq U235 eq./person	4.22E+03
IRP	Land use	pt/person	8.19E+05
SQI	Ozone depletion	kg CFC-11 eq./person	5.23E-02
ADPmm	Particulate matter	disease incidences/person	5.95E-04
ODP	Photochemical ozone formation, human health	kg NMVOC eq./person	4.09E+01
PM	Resource use, fossils	MJ/person	6.50E+04
POCP	Resource use, minerals and metals	kg Sb eq./person	6.36E-02
WDP	Water use	m3 water eq. of deprived water/person	1.15E+04

Table A.2: Weighting factors for EF used in the LCA, taken from Sala et al. (2018)

Acronym	Impact categories	WF [%]
AP	Acidification	0,062
GWP	Climate change	0,2106
ETP	Ecotoxicity, freshwater	0,0192
ADPff	EF-particulate matter	0,0896
EPFW	Eutrophication, freshwater	0,028
EPMW	Eutrophication, marine	0,0296
EPT	Eutrophication, terrestrial	0,0371
HTPc	Human toxicity, cancer	0,0213
HTPnc	Human toxicity, non-cancer	0,0184
IRP	Ionising radiation	0,0501
SQI	Land use	0,0794
ADPmm	Ozone depletion	0,0631
ODP	Photochemical ozone formation	0,0478
PM	Resource depletion, fossils	0,0832
POCP	Resource depletion, minerals and metals	0,0755
WDP	Water use	0,0851

A.2. Life Cycle Inventory

A.2.1. Transport locations and distances

Table A.3: Locations used for the production and construction of the windows.

Product System	Product	Transport	Start	End	Distance (km)
PSW	V_2O_5	lorry	Evraz Highveld mine, ZA	Durban port, ZA	653
PSW	V_2O_5	ship	Durban port, ZA	New York port, NJ, USA	13970
PSW	V_2O_5	lorry	New York port, NJ, USA	Grand Rapids, MI, USA	1196
PSW, DWS and StW	window	lorry	Grand Rapids, MI, USA	New York port, NJ, USA	1019
PSW, DWS and StW	window	ship	New York port, NJ, USA	Rotterdam port, NL	6126
PSW, DWS and StW	window	lorry	Rotterdam port, NL	Amsterdam NL	92

A.2.2. Global parameters

Table A.4: Global input parameters used on OpenLCA in the modelling of the two product systems

Name	Value	Description
A_real_perc	0,06	as ratio. Percentage of area hidden behind the frame
A_vis	9,6	in m2. used exclusively for the inputs of "Lice Cycle" processes
EoL_glass	0	0 = Landfill; 1 = Recycling
ESL_blind	15	in years. Expected service life of the blinds. Determines for how long the blinds are used in a building before being replaced
ESL_glazing	30	in years. Expected service life of the benchmark glazing. Determines for how long the glazing of the benchmark is used in a building before being replaced, together with the frame and all the other components.
ESL_PSW	20	in years. Expected service life of the PSW. Determines for how long the PSW is used in a building before being replaced
f_frac	0,25	Frame fraction, expressed in relation to the visible area A_vis
LS	45	in years. Lifespan of the facade. It is the same in any scenario and option
m_AR	1,14	in g/m2 A_frame. Mass of VO_2 added to 1 m^2 of glazing
proc_glass	0	0 = glass in frame; 1 = glass sheet; 2 = lam. glazing
rho_glass	2500	Density of flatglass in kg/m3
U	0	1 = yes; 0 = no. Decides if B6 stage is accounted for or not
w_frame	80,2	in kg/m2 A_frame. Weight of the of the frame. Value taken from the description of teh used wooden frame (https://v38.ecoquery.ecoinvent.org/Details/LCI/3F011473-CD45-4EB3-9C47-23E8C9E7DB5F/290C1F85-4CC4-4FA1-B0C8-2CB7F4276DCE)
w_glazing	35	in kg/m2 A_vis. Weight of the double glazing
w_plastic	0,94	additional PVB/EVA material in the PSW

Table A.5: Global dependent parameters used on OpenLCA in the modelling of the two product systems

Name	Value	Formula	Description
A_real	1,06	1+ A_real_perc	in m2. Effective quantity of glazing Effective area of the glazing, calculated through a fixed relative increase of the surface
R_blind	2	ceil((LS/ ESL_blind) -1)	Replacement rate of the blinds It is used to determine how many times a blinds must be replaced before the expected removal of the facade. It rounds up the value to an integer E.g.: 30/12 -1 =2.5 - 1 = 1.5 ==>2
R_glazing	1	ceil((LS/ ESL_glazing) -1)	Replacement rate of the BEN glazing. It is used to determine how many times a static window must be replaced before the expected removal of the facade. It rounds up the value to an integer E.g.: 30/12 -1 =2.5 - 1 = 1.5 ==>2
R_PSW	2	ceil((LS /ESL_PSW) -1)	Replacement rate of the PSW It is used to determine how many times a PSW must be replaced before the expected removal of the facade. It rounds up the value to an integer E.g.: 30/12 -1 =2.5 - 1 = 1.5 ==>2
w_ARglazing	35,94	w_glazing + w_plastic	in kg. Weight of the AR glazing
w_PSW	58,15	w_ARglazing * A_real + w_frame * f_frac	in kg. Weight of the Passive Smart Window
w_window	57,15	w_glazing * A_real + w_frame * f_frac	in kg. Weight of the Static Window

A.2.3. PSW

Vanadium Dioxide

Following, the six processes modelled for describing the production of tungsten-doped Vanadium dioxide powder are reported. The first five processes (A.6–A.10) were adapted from Weber et al., while the last one (A.11) was adapted from Sirvent et al. The reference products for each process are reported in italics. Some data were changed from the original because missing or because the updated version was modelled differently on the database. These are reported in bold.

Table A.6: LCI for the production of Vanadium bearing magnetite, from Weber et al. (2018), Supporting information, table S9

Flow type	Flow	Provider	Geography	Amount	Unit
Inputs					
Product	Vanadium pentoxide in ore	V2O5, in magnetite, in crude ore	-	3.40E-02	kg
Product	Titanium dioxide in ore	**ilmenite - magnetite mine operation**	**GLO**	0.25	kg
Product	Iron in ore	Iron,72 % in magnetite,14 % crude ore	**India**	1.08	kg
Product	Infrastructure, mine	**mine construction, vermiculite**	-	3.08E-11	Item(s)
Product	Infrastructure, machine	Market for industrial machine, heavy	GLO	1.22E-05	kg
Product	Infrastructure	Market for conveyor belt	GLO	5.56E-08	m
Product	Diesel	Market for diesel, generator, 10MW	GLO	2.38E-02	**MJ**
Product	Electricity	Market for electricity, medium voltage	ZA	1.44E-02	kWh
Product	Heat	Market for heat, centr. small-scale,nat.gas	RoW	1.54E-02	MJ
Product	Petrol	Market for petrol, unleaded	**ZA**	6.27E-02	kg
Product	Blasting	Market for blasting	GLO	1.55E-04	kg
Product	Recultivation mine	Recultivation, ilmenite mine	GLO	8.29E-05	m^2
Elementary	Occupation	Occupation, mineral extraction site	-	2.49E-03	m^2*a
Elementary	Land use	Transformation, from forest	-	8.29E-05	m^2
Elementary	Land use	Transformation, mineral extraction site	-	8.29E-05	m^2
Outputs					
Product	*Vanadium bearing magnetite*	*Magnetite 72 % Fe, 2.2 % V2O5*		*1.53*	*kg*
Product	Ilmenite	Ilmenite, 54 % titanium dioxide	-	0.46	kg
Elementary	Dust, fine	Particulates, <2.5 um	-	1.77E-05	kg
Elementary	Dust, coarse	Particulates, >10 um	-	2.37E-04	kg
Elementary	Dust, medium	Particulates, >2.5 um, and <10um	-	9.57E-05	kg
Elementary	Water	Water, to air	-	8.79E-03	kg
Elementary	Water	Water, to water	-	4.98E-05	m^3

Table A.7: LCI for the production of Pre-reduced vanadium pentoxide, from Weber et al. (2018), Supporting information, table S10

Flow type	Flow	Provider	Geography	Amount	Unit
Inputs					
Product	Vanadium bearing magnetite	Magnetite, 72 %Fe, 2.2 % V2O5	-	1.53	kg
Product	Dolomite	Market for dolomite	GLO	1.37E-03	kg
Product	Steel	Market for steel, unalloyed	GLO	3.38E-05	kg
Product	Lime	Market for lime	GLO	5.70E-04	kg
Product	Chromium	Market for chromium	GLO	5.97E-06	kg
Product	Lubricating oil	Market for lubricating oil	GLO	4.60E-07	kg
Product	NaOH	**Market for sodium hydroxide, without water, in 50% solution state**	GLO	3.29E-06	kg
Product	Solvent	Market for solvent, organic	GLO	4.00E-09	kg
Product	Coal dust	Market for hard coal	**ZA**	1.30E-02	kg
Product	Infrastructure, factory	Market for aluminum oxide factory	GLO	2.50E-11	Item(s)
Product	Electricity	Market for electricity, high voltage	ZA	2.29E-03	kWh
Product	Electricity	Market for electricity, medium voltage	ZA	2.50E-02	kWh
Product	Heat, natural gas	Market for heat, nat.gas, industrial	RoW	6.55E-02	MJ
Product	Heat, others	Market for heat, other than nat. gas, ind.	RoW	2.33E-02	MJ
Product	Water	Tap water production, conv.	RoW	2.16E-02	kg
Product	Water	Market for water, unspecified	GLO	9.00E-05	m^3
Outputs					
Product	*Pre-reduced V2O5 magnetite*	*Pre-reduced V2O5 bearing magnetite*	-	*1.46*	*kg*
Waste	Waste treatment	**Market for waste mineral oil**	**ZA**	8.66E-08	kg
Waste	Waste treatment	Scrap steel	**RoW**	3.26E-06	kg
Waste	Waste treatment	Spent solvent mixture	**RoW**	1.23E-07	kg
Elementary	As	Arsenic, ion, to water	-	6.20E-12	kg
Elementary	Cd	Cadmium, to air	-	2.10E-10	kg
Elementary	Cd, ion	Cadmium, ion, to water	-	3.10E-12	kg
Elementary	CO2	Carbon dioxide, fossil, to air	-	2.45E-02	kg
Elementary	CO	Carbon monoxide, fossil, to air	-	2.10E-04	kg
Elementary	Cr	Chromium, to air	-	2.70E-09	kg
Elementary	Cr, ion	Chromium, ion, to water	-	4.96E-11	kg
Elementary	Co	Cobalt, to water	-	6.20E-12	kg
Elementary	Cu	Copper, to air	-	4.60E-09	kg
Elementary	Cu, ion	Copper, ion, to water	-	6.20E-12	kg
Elementary	N2O	Dinitrogen monoxide, to air	-	1.50E-09	kg
Elementary	Dioxins	Dioxins, to air	-	5.70E-15	kg
Elementary	Hydrocarbons	Hydrocarbons, aliphatic, to air	-	2.25E-05	kg
Elementary	HCl	Hydrogen chloride, to air	-	2.52E-05	kg
Elementary	HF	Hydrogen fluoride, to air	-	2.04E-05	kg
Elementary	Fe	Iron, ion, to water	-	1.18E-08	kg
Elementary	Pb	Lead, to air	-	6.65E-08	kg
Elementary	Pb	Lead, to water	-	6.20E-12	kg
Elementary	Mn	Manganese, to water	-	1.86E-09	kg
Elementary	Mn	Manganese, to air	-	2.30E-08	kg
Elementary	Hg	Mercury, to air	-	3.49E-10	kg
Elementary	Hg	Mercury, to water	-	8.06E-13	kg
Elementary	CH4	Methane, fossil, to air	-	6.10E-11	kg
Elementary	Ni	Nickel, to air	-	1.50E-08	kg
Elementary	Ni, ion	Nickel, ion, to water	-	6.20E-12	kg
Elementary	Nitrate	Nitrate	-	1.14E-08	kg
Elementary	NOx	Nitrogen oxides, to air	-	3.20E-04	kg
Elementary	NMVOC	NMVOC, to air	-	4.20E-11	kg
Elementary	PAH	PAH, to air	-	1.90E-10	kg
Elementary	Dust, fine	Particulates, <2.5 um, to air	-	7.53E-05	kg
Elementary	Dust, coarse	Particulates, >10 um, to air	-	5.86E-07	kg
Elementary	Dust, medium	Particulates, >2.5 um, <10um, to air	-	4.01E-07	kg
Elementary	P	Phosphorus, to water	-	7.44E-10	kg
Elementary	Ag	Silver, to air	-	5.64E-11	kg
Elementary	SO2	Sulfur dioxide, to air	-	1.31E-04	kg
Elementary	Suspended solids	Suspended solids, to water	-	3.97E-08	kg
Elementary	Water	Water, to water	-	1.84E-05	m3
Elementary	Water	Water, to air	-	3.25E-03	kg
Elementary	Zinc	Zinc	-	5.62E-08	kg
Elementary	Zinc	Zinc, ion	-	2.48E-11	kg

Table A.8: LCI for the production of vanadium pentoxide bearing cast iron, from Weber et al. (2018), Supporting information, table S11

Flow type	Flow	Provider	Geography	Amount	Unit
Inputs					
Product	Pre-reduced V2O5 magnetite	Pre-reduced V2O5 bearing magnetite	-	1.46	kg
Product	Quicklime	Market for quicklime, in pieces, loose	**RoW**	5.50E-02	kg
Product	Coal dust	Market for hard coal	**ZA**	1.40E-02	kg
Product	Oxygen	Market for oxygen, liquid	**RoW**	5.07E-02	kg
Product	Refractory materials	Market for refractory, basic, packed	-	1.35E-02	kg
Product	Equipment	Market for anode, for metal electrolysis	GLO	3.00E-03	kg
Product	Infrastructure	**Market for electric arc furnace converter**	GLO	4.00E-11	Item(s)
Product	Electricity	Market for electricity, medium voltage	ZA	0.42	kWh
Product	Natural gas	Market for natural gas, high pressure	RoW	2.50E-02	m^3
outputs					
Product	*V2O5 bearing cast iron*	*V2O5 bearing cast iron*	-	*1.32*	*kg*
Product	Slag, TiO2	Slag, electric arc furnace steel	-	9.28E-02	kg
Waste	Waste treatment	Inert waste, for final disposal	**RoW**	5.00E-03	kg
Elementary	Benzene	Benzene, to air	-	2.31E-06	kg
Elementary	Cd	Cadmium, to air	-	3.65E-08	kg
Elementary	CO	Carbon monoxide, fossil, to air	-	2.32E-03	kg
Elementary	Cr	Chromium, to air	-	1.25E-06	kg
Elementary	Cu	Copper, to air	-	2.31E-07	kg
Elementary	Dioxins	Dioxins, to air	-	4.54E-12	kg
Elementary	TOC	Hydrocarbons, aromatic, to air	-	7.70E-05	kg
Elementary	HCl	Hydrogen chloride, to air	-	5.20E-06	kg
Elementary	HF	Hydrogen fluoride, to air	-	2.35E-06	kg
Elementary	Pb	Lead, to air	-	1.81E-06	kg
Elementary	Hg	Mercury, to air	-	2.24E-06	kg
Elementary	Ni	Nickel, to air	-	7.01E-07	kg
Elementary	NOx	Nitrogen oxides, to air	-	1.80E-04	kg
Elementary	PAH	Polycyclic aromatic hydrocarbons,to air	-	3.73E-08	kg
Elementary	Dust, fine	Particulates, <2.5 um	-	1.70E-04	kg
Elementary	Dust, coarse	Particulates, >10 um	-	5.86E-05	kg
Elementary	Dust, medium	Particulates, >2.5 um, and <10um	-	1.70E-04	kg
Elementary	Dust, electric arc furnace	Dust, electric arc furnace steel	-	9.60E-03	kg
Elementary	Polychlorinated biphenyls	Polychlorinated biphenyls	-	2.33E-08	kg
Elementary	SO2	Sulfur dioxide, to air	-	7.70E-05	kg
Elementary	Water	Water	-	3.20E-03	m^3
Elementary	Water	Water, to air	-	2.02	kg
Elementary	Zn	Zinc, to air	-	2.29E-05	kg

Table A.9: LCI for the production of in slag from ladle, from Weber et al. (2018), Supporting information, table S12

Flow type	Flow	Provider	Geography	Amount	Unit
Inputs					
Product	*V2O5 bearing cast iron*	*V2O5 bearing cast iron*	-	*1.32*	*kg*
Product	Slag	Slag, electric arc furnace steel	**GLO**	9.28E-02	kg
Product	Lime	Market for quicklime, in pieces, loose	**GLO**	5.50E-02	kg
Product	Dust Coal	Market for hard coal	**ZA**	1.40E-02	kg
Product	Oxygen	Market for oxygen, liquid	**RoW**	5.07E-02	kg
Product	Refractory materials	Market for refractory, basic, packed	-	1.35E-02	kg
Product	Aluminium	**Market for aluminium, wrought alloy**	GLO	1.48E-05	kg
Product	Argon	Market for argon, liquid	GLO	3.29E-03	kg
Product	Cast iron	Market for cast iron	GLO	5.15E-05	kg
Product	Ethylene glycol	Market for ethylene glycol	GLO	3.32E-08	kg
Product	Ferrochromium	Market for FeCr, high-carbon, 68 % Cr	GLO	1.10E-04	kg
Product	Ferromanganese	Market for FeMn, high-coal, 74.5 % Mn	GLO	4.45E-05	kg
Product	Ferrosilicon	Market for ferrosilicon	**GLO**	3.70E-03	kg
Product	MoO3	Market for molybdenum trioxide	GLO	1.41E-05	kg
Product	Nickel	**Market for nickel, class 1**	GLO	3.32E-05	kg
Product	Graphite electrode	Market for anode, for metal electrolysis	GLO	3.00E-03	kg
Product	Infrastructure	Market for electric arc furnace converter	GLO	4.00E-11	Item(s)
Product	Diesel	Market for diesel, burned in build. machine	GLO	3.46E-03	MJ
Product	Propane	Market for propane, burned in build. Mach.	GLO	2.73E-03	MJ
Product	Natural gas	Market for natural gas, high pressure	RoW	2.50E-02	m^3
Product	Electricity	Market for electricity, medium voltage	ZA	0.54	kWh
Product	Electricity	Market for electricity, low voltage	ZA	3.46E-02	kWh
Product	Heat	Market for heat, nat.gas, industrial	RoW	1.23	MJ
Outputs					
Product	*V2O5, in slag from ladle*	*V2O5 in slag, electric arc furnace steel*	-	*6.13E-02*	*kg*
Byproduct	Steel	Steel, low-alloyed	-	1.20	kg
Byproduct	Iron scrap	Iron scrap, unsorted	-	5.15E-05	kg
Byproduct	Slag from furnace	Slag, electric arc furnace steel	-	4.98E-02	kg
Elementary	Water	Water, to air	-	2.92	kg
Elementary	Water	Water	-	2.30E-03	m^3
Waste	Waste treatment	Inert waste, for final disposal	-	5.00E-03	kg
Waste	Waste treatment	Spent solvent mixture	-	3.32E-08	kg
Elementary	Dust, coarse	Particulates, >10 um	-	5.86E-05	kg
Elementary	Dust medium	Particulates, >2.5 um, and <10um	-	1.70E-04	kg
Elementary	Dust fine	Particulates, <2.5 um	-	1.70E-04	kg
Elementary	Dust	Dust, unalloyed electric arc furnace	-	9.60E-03	kg
Elementary	Hg	Mercury, to air	-	2.24E-06	kg
Elementary	Pb	Lead, to air	-	1.81E-06	kg
Elementary	Cr	Chromium, to air	-	1.25E-06	kg
Elementary	Ni	Nickel, to air	-	7.01E-07	kg
Elementary	Zn	Zinc, to air	-	2.29E-05	kg
Elementary	Cd	Cadmium, to air	-	3.65E-08	kg
Elementary	Cu	Copper, to air	-	2.31E-07	kg
Elementary	HF	Hydrogen fluoride, to air	-	2.35E-06	kg
Elementary	HCl	Hydrogen chloride, to air	-	5.20E-06	kg
Elementary	SO2	Sulfur dioxide, to air	-	7.70E-05	kg
Elementary	NOx	Nitrogen oxides, to air	-	1.80E-04	kg
Elementary	CO	Carbon monoxide, fossil, to air	-	2.32E-03	kg
Elementary	TOC	Hydrocarbons, aromatic, to air	-	7.70E-05	kg
Elementary	Benzene	Benzene, to air	-	2.29E-06	kg
Elementary	Hexachlorobenzene	Benzene, hexachloro-, to air	-	2.00E-08	kg
Elementary	PAH	Polycyclic aromatic hydrocarbons,to air	-	3.73E-08	kg
Elementary	PCB	Polychlorinated biphenyls, to air	-	2.33E-08	kg
Elementary	Dioxin	Dioxins, to air	-	4.54E-12	kg
Elementary	Cl	Chloride, to water	-	1.82E-06	kg
Elementary	Cr	Chromium VI, to water	-	1.92E-09	kg
Elementary	Ar	Argon-40, to air	-	3.29E-03	kg

Table A.10: LCI for the production of V_2O_5, from Weber et al. (2018), Supporting information, table S13

Flow type	Flow	Provider	Geography	Amount	Unit
Inputs					
Product	V2O5, in slag (25%)	V2O5, in slag, electric arc furnace steel	-	1.35	kg
Product	Ammonium sulfate	Market for ammonium sulfate	GLO	0.31	kg
Product	Sulfuric acid	Market for sulfuric acid	GLO	0.46	kg
Product	Na2SO4	**Market for sodium hydrogen sulfate**	GLO	0.50	kg
Product	Na2CO3	Market for soda ash	GLO	0.37	kg
Product	Water	Market for water, deionized	GLO	3.16	kg
Product	Electricity	Market for electricity, med. volt.	ZA	0.20	MJ
Product	Heat	Market for heat, nat. gas, industrial	RoW	0.93	MJ
Product	Transport, lorry	Market for transport, freight, lorry unspec.	**ZA**	7.71E-02	t*km
Product	Transport, train	Market for transport, freight, train	**ZA**	0.46	t*km
Outputs					
Product	*Vanadium pentoxide*	*Vanadium pentoxide, for VRFB*	-	*1.00*	*kg*
Byproduct	Iron scrap	Iron scrap, unsorted	-	6.50E-02	kg
Waste	Waste treatment	Spent solvent mixture	**RoW**	6.32E-02	kg
Elementary	SO2	Sulfur dioxide, to air	-	0.23	kg
Elementary	O2	Oxygen	-	5.64E-02	kg
Elementary	CO2	Carbon dioxide, fossil, to air	-	0.16	kg
Elementary	Water	Water, to air	-	8.45E-02	kg
Byproduct	Na2SO4	Sodium sulfate, at plant	-	1.00	kg
Byproduct	Residual slag	Leached slag	-	0.47	kg

Table A.11: LCI for the production of W-doped VO_2 on industrial scale, based on Sirvent et al. (2022), table 5

Flow type	Flow	Provider	Geography	Amount	Unit
Inputs					
Product	V2O5	Vanadium Pentoxide	-	2.16	kg
Product	Transport mine → port (ZA)	Market for transport, freight, lorry, unspecified	ZA	1.41	t*km
Product	**Transport port (ZA)→ port (US)**	Market for transport, freight, sea, container ship	GLO	**30.18**	t*km
Product	**Transport port (US)→ Compound Production site**	Market for transport, freight, lorry, unspecified	**US**	**2.58**	t*km
Product	H2C2O4 - oxalic acid	**Market for oxalic acid**	GLO	2.5	kg
Product	Deionised water	Water production, completely softened	US	495	kg
Product	Ammonium tungstate	Market for ammonium paratungstate	GLO	0.04	kg
Product	Electricity, mixing, 1h (1,5 kWh)	Market for electricity, low voltage	US	62.63	kWh
Product	Electricity, reactor heating, 72h (60,83 kWh)				
Product	Electricity, reactor stirring, 72h (0.29 kWh)				
Product	Electricity, centrifugation (0,01 kWh)				
Product	Electricity, pumping (0,0016 kWh)				
Product	Electricity, drying, 4h (5.20 kWh)				
Outputs					
Product	*W-doped VO2 powder*		-	*1.3*	*kg*
Waste	Acid wastewater	**Market for wastewater, average**	**Row**	495	l
Elementary	CO2	Carbon dioxide, nonfossil	-	1.61	kg
Elementary	CO	Carbon monoxide, nonfossil	-	0.51	kg
Elementary	NH3	Ammonia	-	0.0022	kg

Other processes

Table A.12: 07 Assemble VO2 glazing

Flow type	Flow	Provider	Geography	Amount	Unit
Inputs					
Product	ethylvinylacetate, foil	market for ethylvinylacetate, foil | ethylvinylacetate, foil | Cutoff, S (copy)	GLO	0,52	kg
Product	glazing, double, U<1.1 W/m2K, laminated safety glass	glazing production, double, U<1.1 W/m2K, laminated safety glass | glazing, double, U<1.1 W/m2K, laminated safety glass | Cutoff, S (copy)	RoW	1	m2
Product	W-doped VO2 powder made in US, though hydrothermal synthesis	06 Production of W-doped VO2 powder, through hydrothermal synthesis	-	m_AR	g
Outputs					
Product	*Thermochromic VO2 glazing, in Fremont*		-	*1*	*m2*

Table A.13: PSW window with wooden frame (US)

Flow type	Flow	Provider	Geography	Amount	Unit
Inputs					
Product	electricity, low voltage	market group for electricity, low voltage | electricity, low voltage | Cutoff, S (copy)	US	118/1.82	MJ
Product	packaging film, low density polyethylene	packaging film production, low density polyethylene | packaging film, low density polyethylene | Cutoff, S (copy)	RoW	0.2/1.82	kg
Product	Thermochromic VO2 glazing, in Fremont	07 Assemble VO2 glazing	-	A_real	m2
Product	window frame, wood, U=1.5 W/m2K	window frame production, wood, U=1.5 W/m2K | window frame, wood, U=1.5 W/m2K | Cutoff, S (copy)	RoW	f_frac	m2
Outputs					
Product	*Passive Smart Window with wooden frame, in plant*		-	*1*	*m2*

Table A.14: Transport window to building site, PSW

Flow type	Flow	Provider	Geography	Amount	Unit
Inputs					
Product	transport, freight, lorry 7.5-16 metric ton, EURO6	market for transport, freight, lorry 7.5-16 metric ton, EURO6 | transport, freight, lorry 7.5-16 metric ton, EURO6 | Cutoff, S (copy)	RoW	w_PSW * 1019	kg*km
Product	transport, freight, lorry 7.5-16 metric ton, EURO6	transport, freight, lorry 7.5-16 metric ton, EURO6 | Construction	RER	w_PSW * 92	kg*km
Product	transport, freight, sea, container ship	market for transport, freight, sea, container ship - for window	GLO	w_PSW * 6012	kg*km
Outputs					
Product	*Transport of one window, production to site*		-	*1*	*m2*

Table A.15: End of Life treatment, PSW

Flow type	Flow	Provider	Geography	Amount	Unit
Inputs					
Product	electricity, low voltage	market for electricity, low voltage | electricity, low voltage | Cutoff, S (copy)	NL	w_PSW	MJ
Product	transport, freight, lorry 7.5-16 metric ton, EURO6	transport, freight, lorry 7.5-16 metric ton, EURO6 | EoL	NL	w_PSW * 50	kg*km
Product	transport, freight, lorry 7.5-16 metric ton, EURO6	transport, freight, lorry 7.5-16 metric ton, EURO6 | EoL	NL	w_PSW * 60	kg*km
Outputs					
Product	*AR glazing disposed*		-	*1*	*m2*
Waste	Used double glazing, landfill	Waste glazing to landfill, for PSW	NL	if(Eol_glass = 0; A_real; 0)	m2
Waste	Used double glazing, to sorting	Waste glazing sorting, for PSW	NL	if(Eol_glass = 1; A_real; 0)	m2
Waste	used window frame, wood	market for used window frame, wood | used window frame, wood | Cutoff, S (copy)	GLO	f_frac	m2

Table A.16: Waste glazing to landfill, for PSW

Flow type	Flow	Provider	Geography	Amount	Unit
Inputs					
Waste	*Used double glazing, landfill*		-	*1*	*m2*
Outputs					
Waste	scrap aluminium	market for scrap aluminium | scrap aluminium | Cutoff, S (copy)	Europe w/o Switzerland	1,6185	kg
Elementary	Vanadium to soil		-	m_AR	g
Waste	waste glass	treatment of waste glass, inert material landfill | waste glass | Cutoff, S (copy)	CH	17* rho_glass/ 1000	kg
Waste	waste plastic, mixture	market for waste plastic, mixture | waste plastic, mixture | Cutoff, S (copy)	NL	1.22*1.12	kg
Waste	waste rubber, unspecified	market for waste rubber, unspecified | waste rubber, unspecified | Cutoff, S (copy)	Europe w/o Switzerland	0,5	kg

Table A.17: Waste glazing to sorting, for PSW

Flow type	Flow	Provider	Geography	Amount	Unit
Inputs					
Waste	*Used double glazing, to sorting*		-	*1*	*m2*
Product	electricity, low voltage	market for electricity, low voltage | electricity, low voltage | Cutoff, S (copy)	NL	0,0022	kWh
Product	excavation, hydraulic digger	excavation, hydraulic digger | excavation, hydraulic digger | Cutoff, S (copy)	RER	0,000444	m3
Product	sorting facility, for construction waste	market for sorting facility, for construction waste | sorting facility, for construction waste | Cutoff, S (copy)	GLO	1E-10	Item(s)
Outputs					
Product	Glass cullet, high-quality, for flat glass		-	10/ 100* 17* rho_glass /1000	kg
Product	Glass cullet, low-quality, for glass envelop or fibers		-	89/ 100* 17* rho_glass /1000	kg
Waste	scrap aluminium	market for scrap aluminium | scrap aluminium | Cutoff, S (copy)	Europe w/o Switzerland	1,6185	kg
Elementary	Vanadium to air		-	m_AR	g
Waste	waste glass	treatment of waste glass, inert material landfill | waste glass | Cutoff, S (copy)	CH	1/100* 17* rho_glass/ 1000	kg
Waste	waste plastic, mixture	market for waste plastic, mixture | waste plastic, mixture | Cutoff, S (copy)	NL	1.22*1.12	kg
Waste	waste rubber, unspecified	market for waste rubber, unspecified | waste rubber, unspecified | Cutoff, S (copy)	Europe w/o Switzerland	0,5	kg

Stages

Table A.18: A13 PSW

Flow type	Flow	Provider	Amount	Unit
Inputs				
Product	Passive Smart Window with wooden frame, in Fremont	PSW window with wooden frame (US)	1	m2
Outputs				
Product	*A1-3 - PSW: Production Stage*		*1*	*Item(s)*

Table A.19: A45 PSW

Flow type	Flow	Provider	Amount	Unit
Inputs				
Product	Transport of one window, production to site	Transport Window to building site - PSW	1	m2
Outputs				
Product	*A4-5: Construction Stage*		*1*	*m2*

Table A.20: C14 PSW

Flow type	Flow	Provider	Amount	Unit
Inputs				
Product	AR glazing disposed	End of Life treatment PSW	1	m2
Outputs				
Product	*C - PSW: End-of-Life Stage*		*1*	*Item(s)*

Table A.21: B4 PSW

Flow type	Flow	Provider	Amount	Unit
Inputs				
Product	AR glazing disposed	End of Life treatment PSW	1	m2
Product	Passive Smart Window with wooden frame, in Fremont	PSW with wooden frame	1	m2
Product	Transport of one window, production to site	Transport Window to building site - PSW	1	m2
Outputs				
Product	*B4 - PSW: Replacement*		*1*	*m2*

Table A.22: Life Cycle PSW

Flow type	*Flow*	*Provider*	*Amount*	*Unit*
Inputs				
Product	A1-3 - PSW: Production Stage	A13 PSW	A_vis	m2
Product	A4-5: Construction Stage	A45 PSW	A_vis	m2
Product	B4 - PSW: Replacement	B4 PSW	r_glazing* A_vis	m2
Product	C - PSW: End-of-Life Stage	C14 PSW	A_vis	m2
Product	B6 - PSW: Operational energy Use	B6 - PSW	u	Item(s)
Outputs				
Product	*LC PSW*		*1*	*Item(s)*

A.2.4. DWS

Blind processes from EPD

Table A.23: EPD Result A1-A3 - indoor blind Fisher

Flow type	**Flow**	**Provider**	**Amount**	**Unit**
Outputs				
Product	Blind - Manufactured A1-3		1	m2
Product	Acidification AP equivalent		0,017	Item(s)
Product	Climate Change GWP equivalent		7,86	Item(s)
Product	Ecotoxicity ETP equivalent		56,9	Item(s)
Product	Energy resources ADPff equivalent		139	Item(s)
Product	Eutrophication freshwater EPFW equivalent		3,27E-05	Item(s)
Product	Eutrophication marine EPMW equivalent		0,00382	Item(s)
Product	Eutrophication terrestrial EPT equivalent		0,0407	Item(s)
Product	Human Toxicity cancerous HTPc equivalent		4,95E-09	Item(s)
Product	Human Toxicity non-cancerous HTPnc equivalent		4,25E-07	Item(s)
Product	Ionising Radiation IRP equivalent		1,24	Item(s)
Product	Land use SQP equivalent		80,9	Item(s)
Product	Mineral resources ADPmm equivalent		1,77E-06	Item(s)
Product	Ozone depletion ODP equivalent		4,34E-11	Item(s)
Product	Particulate matter PM equivalent		2,56E-07	Item(s)
Product	Photochemical oxidant POCP equivalent		0,0139	Item(s)
Product	Water use WSP equivalent		0,48	Item(s)

Table A.24: EPD Result C3 - indoor blind Fisher

Flow type	Flow	Provider	Amount	Unit
Outputs				
Product	Blind - Waste processing C3		1	m2
Product	Acidification AP equivalent		0,000045	Item(s)
Product	Climate Change GWP equivalent		0,0299	Item(s)
Product	Ecotoxicity ETP equivalent		0,187	Item(s)
Product	Energy resources ADPff equivalent		0,604	Item(s)
Product	Eutrophication freshwater EPFW equivalent		7,61E-08	Item(s)
Product	Eutrophication marine EPMW equivalent		1,24E-05	Item(s)
Product	Eutrophication terrestrial EPT equivalent		0,000131	Item(s)
Product	Human Toxicity cancerous HTPc equivalent		4,07E-12	Item(s)
Product	Human Toxicity non-cancerous HTPnc equivalent		1,83E-10	Item(s)
Product	Ionising Radiation IRP equivalent		0,0141	Item(s)
Product	Land use SQP equivalent		0,101	Item(s)
Product	Mineral resources ADPmm equivalent		1,73E-09	Item(s)
Product	Ozone depletion ODP equivalent		3,01E-13	Item(s)
Product	Particulate matter PM equivalent		4,02E-10	Item(s)
Product	Photochemical oxidant POCP equivalent		3,41E-05	Item(s)
Product	Water use WSP equivalent		0,00302	Item(s)

Table A.25: EPD Result C4 - indoor blind Fisher

Flow type	Flow	Provider	Amount	Unit
Outputs				
Product	Blind - Disposed C4		1	m2
Product	Acidification AP equivalent		0,017	Item(s)
Product	Climate Change GWP equivalent		7,86	Item(s)
Product	Ecotoxicity ETP equivalent		56,9	Item(s)
Product	Energy resources ADPff equivalent		139	Item(s)
Product	Eutrophication freshwater EPFW equivalent		3,27E-05	Item(s)
Product	Eutrophication marine EPMW equivalent		0,00382	Item(s)
Product	Eutrophication terrestrial EPT equivalent		0,0407	Item(s)
Product	Human Toxicity cancerous HTPc equivalent		4,95E-09	Item(s)
Product	Human Toxicity non-cancerous HTPnc equivalent		4,25E-07	Item(s)
Product	Ionising Radiation IRP equivalent		1,24	Item(s)
Product	Land use SQP equivalent		80,9	Item(s)
Product	Mineral resources ADPmm equivalent		1,77E-06	Item(s)
Product	Ozone depletion ODP equivalent		4,34E-11	Item(s)
Product	Particulate matter PM equivalent		2,56E-07	Item(s)
Product	Photochemical oxidant POCP equivalent		0,0139	Item(s)
Product	Water use WSP equivalent		0,48	Item(s)

Other processes

Table A.26: StW window with wooden frame (US)

Flow type	Flow	Provider	Geography	Amount	Unit
Inputs					
Product	electricity, low voltage	market group for electricity, low voltage | electricity, low voltage | Cutoff, S (copy)	US	118/1.82	MJ
Product	packaging film, low density polyethylene	packaging film production, low density polyethylene | packaging film, low density polyethylene | Cutoff, S (copy)	RoW	0.2/1.82	kg
Product	glazing, double, U<1.1 W/m2K, laminated safety glass	glazing production, double, U<1.1 W/m2K, laminated safety glass | glazing, double, U<1.1 W/m2K, laminated safety glass | Cutoff, S (copy)	RoW	A_real	m2
Product	window frame, wood, U=1.5 W/m2K	window frame production, wood, U=1.5 W/m2K | window frame, wood, U=1.5 W/m2K | Cutoff, S (copy)	RoW	f_frac	m2
Outputs					
Product	*Static Window with wooden frame, in Fremont - US*		-	*1*	*m2*

Table A.27: Transport window to building site, StW

Flow type	Flow	Provider	Geography	Amount	Unit
Inputs					
Product	transport, freight, lorry 7.5-16 metric ton, EURO6	market for transport, freight, lorry 7.5-16 metric ton, EURO6 | transport, freight, lorry 7.5-16 metric ton, EURO6 | Cutoff, S (copy)	RoW	w_window *1019	kg*km
Product	transport, freight, lorry 7.5-16 metric ton, EURO6	transport, freight, lorry 7.5-16 metric ton, EURO6 | Construction	RER	w_window * 92	kg*km
Product	transport, freight, sea, container ship	market for transport, freight, sea, container ship - for window	GLO	w_window * 6012	kg*km
Outputs					
Product	*Transport of one window, production to site*		-	*1*	*m2*

Table A.28: End of Life treatment, StW

Flow type	Flow	Provider	Geography	Amount	Unit
Inputs					
Product	electricity, low voltage	market for electricity, low voltage | electricity, low voltage | Cutoff, S (copy)	NL	w_window	MJ
Product	transport, freight, lorry 7.5-16 metric ton, EURO6	transport, freight, lorry 7.5-16 metric ton, EURO6 | EoL	NL	w_window * 50	kg*km
Product	transport, freight, lorry 7.5-16 metric ton, EURO6	transport, freight, lorry 7.5-16 metric ton, EURO6 | EoL	NL	w_window * 60	kg*km
Outputs					
Product	*static glazing disposed*		-	*1*	*m2*
Waste	Used double glazing, landfill	Waste glazing to landfill, for StW	NL	if(Eol_glass = 0;A_real;0)	m2
Waste	Used double glazing, to sorting	Waste glazing sorting, for StW	NL	if(Eol_glass = 1;A_real;0)	m2
Waste	used window frame, wood	market for used window frame, wood | used window frame, wood | Cutoff, S (copy)	GLO	f_frac	m2

Table A.29: Waste glazing to landfill, for StW

Flow type	Flow	Provider	Geography	Amount	Unit
Inputs					
Waste	*Used double glazing, landfill*		-	*1*	*m2*
Outputs					
Waste	scrap aluminium	market for scrap aluminium | scrap aluminium | Cutoff, S (copy)	Europe w/o Switzer-land	1,6185	kg
Waste	waste glass	treatment of waste glass, inert material landfill | waste glass | Cutoff, S (copy)	CH	17*rho_glass/ 1000	kg
Waste	waste plastic, mixture	market for waste plastic, mixture | waste plas-tic, mixture | Cutoff, S (copy)	NL	1.22*1.12	kg
Waste	waste rubber, unspecified	market for waste rubber, unspecified | waste rubber, unspecified | Cutoff, S (copy)	Europe w/o Switzer-land	0,5	kg

Table A.30: Waste glazing to sorting, for StW

Flow type	Flow	Provider	Geography	Amount	Unit
Inputs					
Waste	*Used double glazing, to sort-ing*		-	*1*	*m2*
Product	electricity, low voltage	market for electricity, low voltage | electricity, low voltage | Cutoff, S (copy)	NL	0,0022	kWh
Product	excavation, hydraulic digger	excavation, hydraulic digger | excavation, hy-draulic digger | Cutoff, S (copy)	RER	0,000444	m3
Product	sorting facility, for construc-tion waste	market for sorting facility, for construction waste | sorting facility, for construction waste | Cutoff, S (copy)	GLO	1E-10	Item(s)
Outputs					
Byproduct	Glass cullet, high-quality, for flat glass		-	10/ 100* 17* rho_glass /1000	kg
Byproduct	Glass cullet, low-quality, for glass envelop or fibers		-	89/ 100* 17* rho_glass /1000	kg
Waste	scrap aluminium	market for scrap aluminium | scrap aluminium | Cutoff, S (copy)	Europe w/o Switzer-land	1,6185	kg
Waste	waste glass	treatment of waste glass, inert material landfill | waste glass | Cutoff, S (copy)	CH	1/100* 17* rho_glass/ 1000	kg
Waste	waste plastic, mixture	market for waste plastic, mixture | waste plas-tic, mixture | Cutoff, S (copy)	NL	1.22*1.12	kg
Waste	waste rubber, unspecified	market for waste rubber, unspecified | waste rubber, unspecified | Cutoff, S (copy)	Europe w/o Switzer-land	0,5	kg

Stages

Table A.31: A45 blind

Flow type	Flow	Provider	Amount	Unit
Inputs				
Product	transport, freight, lorry 7.5-16 metric ton, EURO6	transport, freight, lorry 7.5-16 metric ton, EURO6 | EoL	1.06*50	kg*km
Outputs				
Product	*Blind - Transport to Building A4*		*1*	*m2*

Table A.32: C2 blind - Transport to Waste process

Flow type	Flow	Provider	Amount	Unit
Inputs				
Product	transport, freight, lorry 7.5-16 metric ton, EURO6	transport, freight, lorry 7.5-16 metric ton, EURO6 | EoL	1.06*60	kg*km
Outputs				
Product	*C - StW: End-of-Life Stage*		*1*	*Item(s)*

Table A.33: B4 blind

Flow type	Flow	Provider	Amount	Unit
Inputs				
Product	Blind - Disposed C4	EPD Result C4 - indoor blind Fisher	1	m2
Product	Blind - Manufactured A1-3	EPD Result A1-A3 - indoor blind Fisher	1	m2
Product	Blind - Transport to Building A4	A45 blind	1	m2
Product	Blind - Transport to Waste Processing C2	C2 blind - Transport to Waste Process - blind	1	m2
Product	Blind - Waste processing C3	EPD Result C3 - indoor blind Fisher	1	m2
Outputs				
Product	*Blind - Replacement B4*		*1*	*m2*

Table A.34: A13 StW

Flow type	Flow	Provider	Amount	Unit
Inputs				
Product	Static Window with wooden frame, in Fremont	StW window with wooden frame	1	m2
Outputs				
Product	*A1-3 - StW: Production Stage*		*1*	*Item(s)*

Table A.35: A45 StW

Flow type	Flow	Provider	Amount	Unit
Inputs				
Product	Transport of one window, production to site	Transport Window to building site - StW	1	m2
Outputs				
Product	*A4-5: Construction Stage*		*1*	*m2*

Table A.36: C14 StW

Flow type	Flow	Provider	Amount	Unit
Inputs				
Product	static glazing disposed	End of Life treatment static glazing	1	m2
Outputs				
Product	*C - StW: End-of-Life Stage*		*1*	*Item(s)*

Table A.37: B4 StW

Flow type	Flow	Provider	Amount	Unit
Inputs				
Product	static glazing disposed	End of Life treatment static glazing	1	m2
Product	Static Window with wooden frame, in Fremont	StW with wooden frame	1	m2
Product	Transport of one window, production to site	Transport Window to building site - StW	1	m2
Outputs				
Product	*B4 - StW: Replacement*		*1*	*m2*

Table A.38: Life Cycle blind

Flow type	Flow	Provider	Amount	Unit
Inputs				
Product	Blind - Disposed C4	EPD Result C4 - indoor blind Fisher	A_vis	m2
Product	Blind - Manufactured A1-3	EPD Result A1-A3 - indoor blind Fisher	A_vis	m2
Product	Blind - Replacement B4	B4 blind	r_blind* A_vis	m2
Product	Blind - Transport to Building A4	A45 blind	A_vis	m2
Product	Blind - Transport to Waste Processing C2	C2 blind - Transport to Waste Process	A_vis	m2
Product	Blind - Waste processing C3	EPD Result C3 - indoor blind Fisher	A_vis	m2
Outputs				
Product	*Blind Life Cycle*		*1*	*Item(s)*

Table A.39: Life Cycle StW

Flow type	***Flow***	***Provider***	***Amount***	***Unit***
Inputs				
Product	A1-3 - StW: Production Stage	A13 StW	A_vis	m2
Product	A4-5: Construction Stage	A45 StW	A_vis	m2
Product	B4 - StW: Replacement	B4 StW	r_glazing* A_vis	m2
Product	C - StW: End-of-Life Stage	C14 StW	A_vis	m2
Outputs				
Product	*Static glazing full life cycle*		*1*	*Item(s)*

Table A.40: Life Cycle DWS

Flow type	**Flow**	**Provider**	**Amount**	**Unit**
Inputs				
Product	B6 - DWS: Operational energy Use	B6 - DWS	u	Item(s)
Product	Blind Life Cycle	Life Cycle blind	1	Item(s)
Product	Static glazing full life cycle	Life Cycle StW	1	Item(s)
Outputs				
Product	*Life Cycle - DWS*		*1*	*Item(s)*

B

Appendix - Case Study Results

B.1. Operational Results

Table B.1: Operational impacts of PSW, DWS and StW

		PSW	**DWS**	**StW**
AP	mol H+-Eq	9,52E+01	1,07E+02	9,92E+01
GWP	kg CO2-Eq	4,22E+04	4,75E+04	4,40E+04
ETP	CTUe	7,42E+04	8,34E+04	7,74E+04
ADPff	MJ, net calorific value	5,80E+05	6,52E+05	6,05E+05
EPWF	kg P-Eq	2,20E+01	2,47E+01	2,29E+01
EPT	mol N-Eq	2,41E+02	2,71E+02	2,51E+02
HTPc	CTUh	1,21E-05	1,36E-05	1,26E-05
HTPnc	CTUh	3,75E-04	4,21E-04	3,91E-04
IRP	kBq U235-Eq	3,80E+03	4,27E+03	3,96E+03
SQI	dimensionless	8,57E+04	9,64E+04	8,94E+04
ADPmm	kg Sb-Eq	2,67E-01	3,01E-01	2,79E-01
ODP	kg CFC-11-Eq	2,02E-03	2,27E-03	2,11E-03
PM	disease incidence	3,70E-04	4,16E-04	3,86E-04
POCP	kg NMVOC-Eq	6,37E+01	7,16E+01	6,64E+01
WDP	m3 world eq. deprived	7,65E+03	8,59E+03	7,97E+03
Single Score	-	3,15E+00	3,54E+00	3,29E+00

B.2. Embodied Results

B.2.1. Contribution - baseline scenario

Table B.2: Stage contribution to the embodied impact of PSW

Stage		A13	A45	B4	C14	Total
AP	mol H+-Eq	7,29E+00	1,43E+00	1,82E+01	3,67E-01	2,73E+01
GWP	kg CO2-Eq	1,06E+03	1,69E+02	2,91E+03	2,29E+02	4,37E+03
ETP	CTUe	7,52E+03	8,70E+02	1,79E+04	5,39E+02	2,68E+04
ADPff	MJ, net calorific value	1,35E+04	2,44E+03	3,52E+04	1,65E+03	5,28E+04
EPFW	kg P-Eq	3,62E-01	1,27E-02	8,49E-01	4,98E-02	1,27E+00
EPMW	kg N-Eq	1,34E+00	3,33E-01	3,65E+00	1,51E-01	5,48E+00
EPT	mol N-Eq	1,42E+01	3,68E+00	3,81E+01	1,14E+00	5,71E+01
HTPc	CTUh	9,25E-07	7,09E-08	2,47E-06	2,41E-07	3,71E-06
HTPnc	CTUh	1,45E-05	1,44E-06	3,55E-05	1,80E-06	5,32E-05
IRP	kBq U235-Eq	9,49E+01	1,12E+01	2,32E+02	1,01E+01	3,49E+02
SQI	dimensionless	5,57E+04	1,23E+03	1,15E+05	5,85E+02	1,72E+05
ADPmm	kg Sb-Eq	1,21E-02	5,54E-04	2,67E-02	6,55E-04	4,00E-02
ODP	kg CFC-11-Eq	9,50E-05	3,53E-05	2,81E-04	1,03E-05	4,22E-04
PM	disease incidence	9,11E-05	1,04E-05	2,85E-04	4,08E-05	4,27E-04
POCP	kg NMVOC-Eq	3,98E+00	1,05E+00	1,08E+01	3,45E-01	1,61E+01
WDP	m3 world eq. deprived	3,86E+02	1,08E+01	8,40E+02	2,36E+01	1,26E+03
Single score		1,14E-01	1,53E-02	2,97E-01	1,87E-02	4,45E-01

Table B.3: Stage contribution to the embodied impact of DWS

Stage		A13	A45	B4	C14	Total
AP	mol H+-Eq	7,36E+00	1,41E+00	9,29E+00	3,63E-01	1,84E+01
GWP	kg CO2-Eq	1,12E+03	1,66E+02	1,58E+03	2,18E+02	3,08E+03
ETP	CTUe	8,00E+03	8,56E+02	9,90E+03	4,95E+02	1,92E+04
ADPff	MJ, net calorific value	1,44E+04	2,40E+03	1,98E+04	1,64E+03	3,82E+04
EPFW	kg P-Eq	3,58E-01	1,25E-02	4,20E-01	4,91E-02	8,39E-01
EPMW	kg N-Eq	1,36E+00	3,27E-01	1,87E+00	1,49E-01	3,71E+00
EPT	mol N-Eq	1,44E+01	3,62E+00	1,95E+01	1,12E+00	3,87E+01
HTPc	CTUh	9,64E-07	6,97E-08	1,32E-06	2,39E-07	2,59E-06
HTPnc	CTUh	1,82E-05	1,42E-06	2,53E-05	1,63E-06	4,65E-05
IRP	kBq U235-Eq	1,05E+02	1,10E+01	1,39E+02	1,01E+01	2,65E+02
SQI	dimensionless	5,64E+04	1,21E+03	5,89E+04	5,81E+02	1,17E+05
ADPmm	kg Sb-Eq	1,20E-02	5,45E-04	1,33E-02	6,44E-04	2,65E-02
ODP	kg CFC-11-Eq	9,41E-05	3,47E-05	1,39E-04	1,02E-05	2,78E-04
PM	disease incidence	9,28E-05	1,03E-05	1,46E-04	4,08E-05	2,90E-04
POCP	kg NMVOC-Eq	4,05E+00	1,03E+00	5,56E+00	3,41E-01	1,10E+01
WDP	m3 world eq. deprived	3,77E+02	1,06E+01	4,15E+02	2,29E+01	8,25E+02
Single score		1,18E-01	1,51E-02	1,57E-01	1,83E-02	3,09E-01

Table B.4: Stage contribution to the embodied impact of StW

Stage		A13	A45	B4	C14	Total
AP	mol H+-Eq	7,19E+00	1,41E+00	8,96E+00	3,61E-01	1,79E+01
GWP	kg CO2-Eq	1,04E+03	1,66E+02	1,42E+03	2,17E+02	2,85E+03
ETP	CTUe	7,45E+03	8,55E+02	8,79E+03	4,86E+02	1,76E+04
ADPff	MJ, net calorific value	1,31E+04	2,39E+03	1,71E+04	1,62E+03	3,41E+04
EPFW	kg P-Eq	3,57E-01	1,25E-02	4,19E-01	4,90E-02	8,37E-01
EPMW	kg N-Eq	1,32E+00	3,27E-01	1,80E+00	1,48E-01	3,60E+00
EPT	mol N-Eq	1,40E+01	3,62E+00	1,88E+01	1,12E+00	3,75E+01
HTPc	CTUh	9,17E-07	6,97E-08	1,23E-06	2,39E-07	2,45E-06
HTPnc	CTUh	1,41E-05	1,41E-06	1,71E-05	1,60E-06	3,42E-05
IRP	kBq U235-Eq	9,35E+01	1,10E+01	1,15E+02	9,97E+00	2,29E+02
SQI	dimensionless	5,56E+04	1,21E+03	5,74E+04	5,79E+02	1,15E+05
ADPmm	kg Sb-Eq	1,20E-02	5,45E-04	1,32E-02	6,44E-04	2,64E-02
ODP	kg CFC-11-Eq	9,41E-05	3,47E-05	1,39E-04	1,02E-05	2,78E-04
PM	disease incidence	9,04E-05	1,03E-05	1,41E-04	4,08E-05	2,83E-04
POCP	kg NMVOC-Eq	3,91E+00	1,03E+00	5,29E+00	3,39E-01	1,06E+01
WDP	m3 world eq. deprived	3,72E+02	1,06E+01	4,06E+02	2,29E+01	8,11E+02
Single score		1,12E-01	1,51E-02	1,46E-01	1,82E-02	2,91E-01

Table B.5: Process contribution to the embodied impact of PSW

Process		others	VO2 production	Lorry, NL - Window to site	EVA EoL	Lorry, NL - Window EoL	EVA Production	Ship - Window to site	Electricity NL - Window EoL	Electricity US - Frame add	Waste market - Frame EoL	Lorry, US - Window to site	Frame Production	Glazing Production	Total
AP	mol H+-Eq	1,24E-01	7,90E-02	9,30E-02	2,45E-02	1,11E-01	2,05E-01	3,08E+00	6,02E-01	9,03E-01	2,83E-01	1,13E+00	7,80E+00	1,28E+01	2,73E+01
GWP	kg CO2-Eq	1,60E+02	4,63E+00	3,26E+01	9,67E+01	3,90E+01	4,65E+01	9,42E+01	2,68E+02	2,64E+02	1,31E+02	3,80E+02	1,27E+03	1,58E+03	4,37E+03
ETP	CTUe	4,47E+02	2,54E+01	1,79E+02	1,93E+02	2,14E+02	1,88E+02	3,54E+02	5,13E+02	1,67E+03	2,75E+02	2,08E+03	8,21E+03	1,24E+04	2,68E+04
ADPff	MJ, net calorific value	4,92E+02	6,71E+01	4,95E+02	2,43E+01	5,92E+02	1,33E+03	1,22E+03	3,69E+03	4,58E+03	4,23E+02	5,59E+03	1,50E+04	1,93E+04	5,28E+04
EPFW	kg P-Eq	3,38E-03	2,54E-03	2,48E-03	3,12E-04	2,96E-03	1,12E-02	3,10E-03	1,40E-01	2,03E-01	5,74E-03	3,24E-02	4,67E-01	4,00E-01	1,27E+00
EPMW	kg N-Eq	3,93E-02	1,61E-02	1,82E-02	1,59E-02	2,17E-02	4,17E-02	7,58E-01	1,59E-01	1,61E-01	2,25E-01	2,22E-01	1,57E+00	2,23E+00	5,48E+00
EPT	mol N-Eq	4,23E-01	1,75E-01	1,98E-01	1,16E-01	2,37E-01	4,32E-01	8,42E+00	1,53E+00	1,35E+00	1,20E+00	2,42E+00	1,54E+01	2,52E+01	5,71E+01
HTPc	CTUh	7,77E-09	9,92E-09	1,38E-08	8,92E-09	1,66E-08	1,49E-08	4,15E-08	7,66E-08	8,91E-08	6,15E-07	1,57E-07	1,58E-06	1,08E-06	3,71E-06
HTPnc	CTUh	6,25E-07	8,24E-07	3,17E-07	3,00E-07	3,80E-07	3,85E-07	3,13E-07	2,38E-06	2,32E-06	1,79E-06	3,69E-06	2,02E-05	1,96E-05	5,32E-05
IRP	kBq U235-Eq	1,71E+00	4,60E-01	2,61E+00	8,52E-02	3,13E+00	3,60E+00	5,47E+00	2,41E+01	9,65E+01	2,01E+00	2,55E+01	8,20E+01	1,01E+02	3,49E+02
SQP	dimensionless	4,66E+02	1,70E+01	2,91E+02	1,13E+01	3,48E+02	2,12E+02	1,64E+02	5,45E+02	7,96E+02	4,25E+02	3,25E+03	1,59E+05	7,32E+03	1,72E+05
ADPmm	kg Sb-Eq	6,73E-05	3,16E-05	1,27E-04	9,19E-06	1,51E-04	2,87E-04	1,02E-04	1,70E-03	1,66E-03	8,27E-05	1,43E-03	1,73E-02	1,71E-02	4,00E-02
ODP	kg CFC-11-Eq	3,50E-06	2,70E-07	7,41E-06	3,01E-07	8,86E-06	2,38E-06	1,88E-05	1,28E-05	1,51E-05	5,77E-06	7,98E-05	7,25E-05	1,95E-04	4,22E-04
PM	disease incidence	1,90E-06	2,53E-07	2,24E-06	1,83E-07	2,68E-06	1,93E-06	2,95E-06	2,35E-06	4,82E-06	1,16E-04	2,61E-05	1,24E-04	1,42E-04	4,27E-04
POCP	kg NMVOC-Eq	1,32E-01	3,51E-02	7,59E-02	2,86E-02	9,08E-02	1,58E-01	2,18E+00	4,04E-01	4,04E-01	4,19E-01	9,02E-01	4,76E+00	6,54E+00	1,61E+01
WDP	m3 world eq. deprived	1,37E+01	1,63E+00	2,51E+00	3,84E+00	3,00E+00	3,96E+01	3,52E+00	4,86E+01	5,58E+01	8,76E+00	2,64E+01	5,31E+02	5,22E+02	1,26E+03
Single score		6,39E-03	6,83E-04	2,55E-03	3,03E-03	3,04E-03	4,89E-03	1,41E-02	2,00E-02	2,41E-02	2,45E-02	2,94E-02	1,50E-01	1,62E-01	4,45E-01

Table B.6: Process contribution to the embodied impact of DSW

Process		others	Blind EoL	Lorry, NL - Window to site	Lorry, NL - Window EoL	Ship - Window to site	Electricity NL - Window EoL	Electricity US - Frame add	Waste market - Frame EoL	Blind Production	Lorry, US - Window to site	Frame Production	Glazing Production	Total
AP	mol H+-Eq	9,31E-02	6,41E-03	6,10E-02	7,49E-02	2,02E+00	3,95E-01	6,02E-01	1,88E-01	4,90E-01	7,41E-01	5,20E+00	8,55E+00	1,84E+01
GWP	kg CO2-Eq	1,51E+02	2,59E+00	2,14E+01	2,63E+01	6,17E+01	1,76E+02	1,76E+02	8,77E+01	2,26E+02	2,49E+02	8,50E+02	1,05E+03	3,08E+03
ETP	CTUe	3,27E+02	2,62E+01	1,17E+02	1,44E+02	2,32E+02	3,36E+02	1,11E+03	1,84E+02	1,64E+03	1,36E+03	5,48E+03	8,29E+03	1,92E+04
ADPff	MJ, net calorific value	3,33E+02	4,30E+01	3,25E+02	3,99E+02	7,99E+02	2,42E+03	3,05E+03	2,82E+02	4,00E+03	3,66E+03	9,99E+03	1,29E+04	3,82E+04
EPFW	kg P-Eq	2,36E-03	2,84E-04	1,62E-03	2,00E-03	2,03E-03	9,15E-02	1,35E-01	3,83E-03	9,42E-04	2,12E-02	3,11E-01	2,67E-01	8,39E-01
EPMW	kg N-Eq	3,33E-02	1,49E-03	1,19E-02	1,46E-02	4,97E-01	1,04E-01	1,08E-01	1,50E-01	1,10E-01	1,46E-01	1,05E+00	1,49E+00	3,71E+00
EPT	mol N-Eq	3,33E-01	1,62E-02	1,30E-01	1,59E-01	5,52E+00	1,00E+00	8,99E-01	8,02E-01	1,17E+00	1,58E+00	1,03E+01	1,68E+01	3,87E+01
HTPc	CTUh	9,10E-09	1,15E-09	9,07E-09	1,11E-08	2,72E-08	5,02E-08	5,94E-08	4,10E-07	1,43E-07	1,03E-07	1,05E-06	7,17E-07	2,59E-06
HTPnc	CTUh	2,40E-07	8,13E-08	2,08E-07	2,56E-07	2,05E-07	1,56E-06	1,55E-06	1,19E-06	1,22E-05	2,42E-06	1,35E-05	1,31E-05	4,65E-05
IRP	kBq U235-Eq	1,15E+00	4,72E-01	1,71E+00	2,11E+00	3,58E+00	1,58E+01	6,44E+01	1,34E+00	3,57E+01	1,67E+01	5,47E+01	6,76E+01	2,65E+02
SQP	dimensionless	3,12E+02	8,09E+00	1,91E+02	2,35E+02	1,07E+02	3,57E+02	5,31E+02	2,83E+02	2,33E+03	2,13E+03	1,06E+05	4,88E+03	1,17E+05
ADPmm	kg Sb-Eq	4,76E-05	1,59E-06	8,29E-05	1,02E-04	6,71E-05	1,11E-03	1,11E-03	5,51E-05	5,10E-05	9,40E-04	1,15E-02	1,14E-02	2,65E-02
ODP	kg CFC-11-Eq	2,39E-06	8,81E-08	4,86E-06	5,97E-06	1,23E-05	8,41E-06	1,01E-05	3,85E-06	1,25E-09	5,23E-05	4,83E-05	1,30E-04	2,78E-04
PM	disease incidence	1,32E-06	7,71E-08	1,47E-06	1,81E-06	1,93E-06	1,54E-06	3,22E-06	7,72E-05	7,37E-06	1,71E-05	8,28E-05	9,45E-05	2,90E-04
POCP	kg NMVOC-Eq	1,00E-01	4,79E-03	4,97E-02	6,11E-02	1,43E+00	2,65E-01	2,69E-01	2,79E-01	4,00E-01	5,91E-01	3,17E+00	4,36E+00	1,10E+01
WDP	m3 world eq. deprived	1,08E+01	9,92E-02	1,64E+00	2,02E+00	2,31E+00	3,18E+01	3,72E+01	5,84E+00	1,38E+01	1,73E+01	3,54E+02	3,48E+02	8,25E+02
Single score		5,56E-03	1,93E-04	1,67E-03	2,05E-03	9,21E-03	1,31E-02	1,61E-02	1,63E-02	1,73E-02	1,93E-02	1,00E-01	1,08E-01	3,09E-01

Table B.7: Process contribution to the embodied impact of StW

Process		others	Lorry, NL - Window to site	Lorry, NL - Window EoL	Ship - Window to site	Electricity NL - Window EoL	Electricity US - Frame add	Waste market - Frame EoL	Lorry, US - Window to site	Frame Production	Glazing Production	Total
AP	mol H+-Eq	9,31E-02	6,10E-02	7,49E-02	2,02E+00	3,95E-01	6,02E-01	1,88E-01	7,41E-01	5,20E+00	8,55E+00	1,84E+01
GWP	kg CO2-Eq	1,51E+02	2,14E+01	2,63E+01	6,17E+01	1,76E+02	1,76E+02	8,77E+01	2,49E+02	8,50E+02	1,05E+03	3,08E+03
ETP	CTUe	3,27E+02	1,17E+02	1,44E+02	2,32E+02	3,36E+02	1,11E+03	1,84E+02	1,36E+03	5,48E+03	8,29E+03	1,92E+04
ADPff	MJ, net calorific value	3,33E+02	3,25E+02	3,99E+02	7,99E+02	2,42E+03	3,05E+03	2,82E+02	3,66E+03	9,99E+03	1,29E+04	3,82E+04
EPFW	kg P-Eq	2,36E-03	1,62E-03	2,00E-03	2,03E-03	9,15E-02	1,35E-01	3,83E-03	2,12E-02	3,11E-01	2,67E-01	8,39E-01
EPMW	kg N-Eq	3,33E-02	1,19E-02	1,46E-02	4,97E-01	1,04E-01	1,08E-01	1,50E-01	1,46E-01	1,05E+00	1,49E+00	3,71E+00
EPT	mol N-Eq	3,33E-01	1,30E-01	1,59E-01	5,52E+00	1,00E+00	8,99E-01	8,02E-01	1,58E+00	1,03E+01	1,68E+01	3,87E+01
HTPc	CTUh	9,10E-09	9,07E-09	1,11E-08	2,72E-08	5,02E-08	5,94E-08	4,10E-07	1,03E-07	1,05E-06	7,17E-07	2,59E-06
HTPnc	CTUh	2,40E-07	2,08E-07	2,56E-07	2,05E-07	1,56E-06	1,55E-06	1,19E-06	2,42E-06	1,35E-05	1,31E-05	4,65E-05
IRP	kBq U235-Eq	1,15E+00	1,71E+00	2,11E+00	3,58E+00	1,58E+01	6,44E+01	1,34E+00	1,67E+01	5,47E+01	6,76E+01	2,65E+02
SQP	dimensionless	3,12E+02	1,91E+02	2,35E+02	1,07E+02	3,57E+02	5,31E+02	2,83E+02	2,13E+03	1,06E+05	4,88E+03	1,17E+05
ADPmm	kg Sb-Eq	4,76E-05	8,29E-05	1,02E-04	6,71E-05	1,11E-03	1,11E-03	5,51E-05	9,40E-04	1,15E-02	1,14E-02	2,65E-02
ODP	kg CFC-11-Eq	2,39E-06	4,86E-06	5,97E-06	1,23E-05	8,41E-06	1,01E-05	3,85E-06	5,23E-05	4,83E-05	1,30E-04	2,78E-04
PM	disease incidence	1,32E-06	1,47E-06	1,81E-06	1,93E-06	1,54E-06	3,22E-06	7,72E-05	1,71E-05	8,28E-05	9,45E-05	2,90E-04
POCP	kg NMVOC-Eq	1,00E-01	4,97E-02	6,11E-02	1,43E+00	2,65E-01	2,69E-01	2,79E-01	5,91E-01	3,17E+00	4,36E+00	1,10E+01
WDP	m3 world eq. deprived	1,08E+01	1,64E+00	2,02E+00	2,31E+00	3,18E+01	3,72E+01	5,84E+00	1,73E+01	3,54E+02	3,48E+02	8,25E+02
Single score		5,56E-03	1,67E-03	2,05E-03	9,21E-03	1,31E-02	1,61E-02	1,63E-02	1,93E-02	1,00E-01	1,08E-01	3,09E-01

B.2.2. Scenarios results

Table B.8: Results for the Expected Service Life (ESL) Scenarios

Category	Unit	PSW			DWS				StW
		PSW-12	PSW-20	PSW-30	blind-10	blind-15	blind-30	blind-45	-
AP	mol H+-Eq	3,64E+01	2,73E+01	1,82E+01	1,87E+01	1,84E+01	1,82E+01	1,81E+01	1,79E+01
GWP	kg CO2-Eq	5,83E+03	4,37E+03	2,91E+03	3,22E+03	3,07E+03	3,00E+03	2,92E+03	2,84E+03
ETP	CTUe	3,57E+04	2,68E+04	1,79E+04	2,03E+04	1,92E+04	1,86E+04	1,81E+04	1,75E+04
ADPff	MJ, net calorific value	7,04E+04	5,28E+04	3,52E+04	4,09E+04	3,82E+04	3,68E+04	3,55E+04	3,41E+04
EPFW	kg P-Eq	1,70E+00	1,27E+00	8,49E-01	8,38E-01	8,37E-01	8,37E-01	8,37E-01	8,36E-01
EPMW	kg N-Eq	7,30E+00	5,48E+00	3,65E+00	3,78E+00	3,71E+00	3,67E+00	3,63E+00	3,60E+00
EPT	mol N-Eq	7,62E+01	5,71E+01	3,81E+01	3,95E+01	3,87E+01	3,83E+01	3,79E+01	3,75E+01
HTPc	CTUh	4,95E-06	3,71E-06	2,47E-06	2,69E-06	2,59E-06	2,55E-06	2,50E-06	2,45E-06
HTPnc	CTUh	7,09E-05	5,32E-05	3,55E-05	5,47E-05	4,65E-05	4,23E-05	3,82E-05	3,41E-05
IRP	kBq U235-Eq	4,65E+02	3,49E+02	2,32E+02	2,92E+02	2,68E+02	2,56E+02	2,43E+02	2,31E+02
SQI	-	2,30E+05	1,72E+05	1,15E+05	1,19E+05	1,17E+05	1,16E+05	1,16E+05	1,15E+05
ADPmm	kg Sb-Eq	5,34E-02	4,00E-02	2,67E-02	2,65E-02	2,65E-02	2,65E-02	2,65E-02	2,64E-02
ODP	kg CFC-11-Eq	5,63E-04	4,22E-04	2,81E-04	2,80E-04	2,80E-04	2,80E-04	2,80E-04	2,80E-04
PM	disease incidence	5,70E-04	4,27E-04	2,85E-04	2,95E-04	2,90E-04	2,87E-04	2,85E-04	2,82E-04
POCP	kg NMVOC-Eq	2,15E+01	1,61E+01	1,08E+01	1,12E+01	1,10E+01	1,08E+01	1,07E+01	1,06E+01
WDP	m3 world eq. deprived	1,68E+03	1,26E+03	8,40E+02	8,36E+02	8,26E+02	8,22E+02	8,17E+02	8,13E+02
Single Score	-	5,93E-01	4,45E-01	2,97E-01	3,20E-01	3,09E-01	3,03E-01	2,97E-01	2,91E-01

Table B.9: Results for the VO_2 Scenarios

Category	Unit	m1	m2	m3	m4	m5
AP	mol H+-Eq	2,71E+01	2,72E+01	2,73E+01	2,75E+01	2,77E+01
GWP	kg CO2-Eq	4,35E+03	4,35E+03	4,35E+03	4,37E+03	4,39E+03
ETP	CTUe	2,66E+04	2,66E+04	2,67E+04	2,68E+04	2,70E+04
ADPff	MJ, net calorific value	5,26E+04	5,27E+04	5,27E+04	5,29E+04	5,32E+04
EPFW	kg P-Eq	1,27E+00	1,27E+00	1,27E+00	1,27E+00	1,27E+00
EPMW	kg N-Eq	5,46E+00	5,49E+00	5,51E+00	5,59E+00	5,68E+00
EPT	mol N-Eq	5,70E+01	5,72E+01	5,75E+01	5,83E+01	5,93E+01
HTPc	CTUh	3,70E-06	3,70E-06	3,70E-06	3,71E-06	3,73E-06
HTPnc	CTUh	5,21E-05	5,25E-05	5,30E-05	5,43E-05	5,59E-05
IRP	kBq U235-Eq	3,51E+02	3,51E+02	3,52E+02	3,52E+02	3,53E+02
SQI	dimensionless	1,72E+05	1,72E+05	1,72E+05	1,72E+05	1,72E+05
ADPmm	kg Sb-Eq	4,00E-02	4,00E-02	4,00E-02	4,00E-02	4,01E-02
ODP	kg CFC-11-Eq	4,23E-04	4,24E-04	4,25E-04	4,27E-04	4,30E-04
PM	disease incidence	4,25E-04	4,26E-04	4,26E-04	4,26E-04	4,27E-04
POCP	kg NMVOC-Eq	1,61E+01	1,62E+01	1,62E+01	1,64E+01	1,67E+01
WDP	m3 world eq. deprived	1,26E+03	1,26E+03	1,26E+03	1,26E+03	1,27E+03
Single Score	-	4,43E-01	4,44E-01	4,44E-01	4,46E-01	4,48E-01

Table B.10: Results for the End of Life (EoL) Scenarios

Category	Unit	PSW		DWS		StW	
		Landfill	Recycling	Landfill	Recycling	Landfill	Recycling
AP	mol H+-Eq	2,74E+01	2,73E+01	1,84E+01	1,84E+01	1,79E+01	1,79E+01
GWP	kg CO2-Eq	4,38E+03	4,37E+03	3,08E+03	3,07E+03	2,85E+03	2,85E+03
ETP	CTUe	2,68E+04	2,68E+04	1,92E+04	1,92E+04	1,76E+04	1,76E+04
ADPff	MJ, net calorific value	5,29E+04	5,28E+04	3,82E+04	3,81E+04	3,41E+04	3,40E+04
EPFW	kg P-Eq	1,27E+00	1,27E+00	8,39E-01	8,38E-01	8,37E-01	8,37E-01
EPMW	kg N-Eq	5,54E+00	5,52E+00	3,71E+00	3,69E+00	3,60E+00	3,58E+00
EPT	mol N-Eq	5,78E+01	5,75E+01	3,87E+01	3,86E+01	3,75E+01	3,74E+01
HTPc	CTUh	3,71E-06	3,71E-06	2,59E-06	2,59E-06	2,45E-06	2,45E-06
HTPnc	CTUh	5,32E-05	5,32E-05	4,65E-05	4,65E-05	3,42E-05	3,42E-05
IRP	kBq U235-Eq	3,49E+02	3,48E+02	2,65E+02	2,65E+02	2,29E+02	2,28E+02
SQI	-	1,72E+05	1,72E+05	1,17E+05	1,17E+05	1,15E+05	1,15E+05
ADPmm	kg Sb-Eq	4,00E-02	4,00E-02	2,65E-02	2,65E-02	2,64E-02	2,64E-02
ODP	kg CFC-11-Eq	4,24E-04	4,21E-04	2,78E-04	2,76E-04	2,78E-04	2,76E-04
PM	disease incidence	4,27E-04	4,26E-04	2,90E-04	2,90E-04	2,83E-04	2,82E-04
POCP	kg NMVOC-Eq	1,63E+01	1,62E+01	1,10E+01	1,09E+01	1,06E+01	1,05E+01
WDP	m3 world eq. deprived	1,26E+03	1,26E+03	8,25E+02	8,25E+02	8,11E+02	8,11E+02
Single Score	-	4,46E-01	4,45E-01	3,09E-01	3,08E-01	2,91E-01	2,91E-01

B.2.3. Monte Carlo simulation

Table B.11: Embodied impact final results from the Monte Carlo simulation, with standard deviation

		Results						Weighted results					
		PSW		DWS		StW		PSW		DWS		StW	
Category	**Reference unit**	**Mean**	**σ**	**Mean**	**σ**	**Mean**	**σ**	**Value**	**σ**	**Value**	**σ**	**Value**	**σ**
AP	mol H+-Eq	2,65E+01	2,96E+00	1,83E+01	7,89E-01	1,79E+01	8,10E-01	2,96E-02	3,30E-03	2,04E-02	8,80E-04	2,00E-02	9,04E-04
GWP	kg CO2-Eq	3,97E+03	4,52E+02	2,86E+03	1,39E+02	2,69E+03	1,39E+02	1,11E-01	1,26E-02	7,97E-02	3,88E-03	7,50E-02	3,88E-03
ETP	CTUe	2,55E+04	2,85E+03	1,85E+04	8,06E+02	1,73E+04	7,95E+02	8,64E-03	9,65E-04	6,28E-03	2,73E-04	5,86E-03	2,69E-04
ADPff	MJ, net calorific value	5,13E+04	5,74E+03	3,72E+04	1,65E+03	3,42E+04	1,60E+03	6,57E-02	7,34E-03	4,76E-02	2,11E-03	4,38E-02	2,05E-03
EPFW	kg P-Eq	1,24E+00	1,41E-01	8,38E-01	4,28E-02	8,38E-01	4,42E-02	2,15E-02	2,46E-03	1,46E-02	7,44E-04	1,46E-02	7,68E-04
EPMW	kg N-Eq	5,35E+00	6,06E-01	3,67E+00	1,77E-01	3,59E+00	1,82E-01	8,13E-03	9,20E-04	5,57E-03	2,69E-04	5,45E-03	2,76E-04
EPT	mol N-Eq	5,58E+01	6,24E+00	3,83E+01	1,69E+00	3,75E+01	1,74E+00	1,17E-02	1,31E-03	8,03E-03	3,55E-04	7,85E-03	3,65E-04
HTPc	CTUh	3,61E-06	4,52E-07	2,56E-06	1,85E-07	2,46E-06	1,90E-07	4,44E-03	5,57E-04	3,15E-03	2,28E-04	3,02E-03	2,34E-04
HTPnc	CTUh	5,16E-05	5,99E-06	4,32E-05	2,60E-06	3,42E-05	2,02E-06	7,36E-03	8,55E-04	6,16E-03	3,70E-04	4,87E-03	2,88E-04
IRP	kBq U235-Eq	3,39E+02	3,70E+01	2,56E+02	9,78E+00	2,29E+02	8,66E+00	4,02E-03	4,39E-04	3,04E-03	1,16E-04	2,72E-03	1,03E-04
SQI	dimensionless	1,68E+05	2,50E+04	1,16E+05	1,29E+04	1,15E+05	1,33E+04	1,63E-02	2,42E-03	1,13E-02	1,25E-03	1,11E-02	1,29E-03
ADPmm2	kg Sb-Eq	3,89E-02	4,53E-03	2,65E-02	1,49E-03	2,65E-02	1,53E-03	4,62E-02	5,38E-03	3,14E-02	1,76E-03	3,14E-02	1,82E-03
ODP	kg CFC-11-Eq	4,10E-04	4,46E-05	2,79E-04	9,73E-06	2,79E-04	1,01E-05	4,95E-04	5,38E-05	3,37E-04	1,17E-05	3,37E-04	1,21E-05
PM	disease incidence	4,15E-04	5,13E-05	2,89E-04	2,02E-05	2,84E-04	2,09E-05	6,25E-02	7,73E-03	4,35E-02	3,05E-03	4,27E-02	3,14E-03
POCP	kg NMVOC-Eq	1,58E+01	1,78E+00	1,09E+01	5,18E-01	1,06E+01	5,31E-01	1,84E-02	2,08E-03	1,27E-02	6,06E-04	1,24E-02	6,21E-04
WDP	m3 world eq. deprived	1,21E+03	1,41E+02	8,15E+02	4,56E+01	8,06E+02	4,70E+01	8,99E-03	1,04E-03	6,03E-03	3,37E-04	5,96E-03	3,48E-04
Single Score	-	-						0,423	0,019	0,300	0,006	0,286	0,006