LCA framework for assessing the climate impact of window reuse in the early design phase

Master's thesis in Industrial Ecology

OLIVIA CARLSSON

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2026
www.chalmers.se

Master's thesis 2026

LCA framework for assessing the climate impact of window reuse in the early design phase

OLIVIA CARLSSON

Department of Architecture and Civil Engineering
Division of Sustainable Built Environments
Chalmers University of Technology
Gothenburg, Sweden 2026

OLIVIA CARLSSON

Supervisor: Aida Eghbali , Department of Architecture and Civil Engineering
Examiner: Alexander Hollberg , Department of Architecture and Civil Engineering

Master's Thesis 2026
Department of Architecture and Civil Engineering
Division of Sustainable Built Environments
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Gothenburg, Sweden 2026

LCA framework for assessing the climate impact of window reuse in the early design phase
OLIVIA CARLSSON
Department of Architecture and Civil Engineering
Chalmers University of Technology

Abstract

The construction sector accounts for a large share of global greenhouse gas emissions and embodied emissions make up a growing part of this impact. One way to reduce embodied emissions is to reuse building components, and windows have been identified as one of the components with the greatest potential for reuse. However, as windows are part of the building envelope reusing them may increase the operational energy use of the building, which can offset the savings in embodied emissions. Whether reuse of windows actually lowers the climate impact therefore has to be assessed through a life cycle assessment (LCA), but no established method exists for modeling reused building components. This assessment is also needed already in the early design phase since the choices made at this stage have the greatest influence on the building's overall carbon footprint. Conducting a full LCA at this point is however not feasible, as many alternatives must be compared quickly and the data available on the reused window is often limited.

This thesis therefore develops a simplified LCA-based method for comparing the global warming potential of a reused and a newly manufactured window in the early design phase. The method follows the cut-off allocation method, covers modules A1-A4, B4, B6 and C4, and reports GWP-fossil per m2 of window over a 50-year reference study period. As no environmental product declaration (EPD) is typically available for reused windows, a geometry-based framework is used to estimate the material quantities from the window dimensions. The method was developed and tested through a case study of a 1960s coupled wooden window, complemented by a sensitivity analysis of the governing parameters.

The case study demonstrates that the method can be applied under limited data availability. The sensitivity analysis identifies a small set of parameters that govern the result and must be specified by the user, namely the U-value and reference service life of the reused window, the local district heating emission factor and the annual degree-hours. The transport distance has a smaller influence and only needs to be roughly estimated, while the remaining parameters have a negligible effect and can be assigned default values. The framework additionally requires a few window dimensions, but these can easily be measured directly from the window without any material documentation.

Keywords: Life cycle assessment, LCA, Window, Reuse, Climate impact, Early design phase

Acknowledgements

First, I would like to thank my supervisor Aida Eghbali. Thank you for your guidance and encouragement throughout this thesis, for always taking the time to discuss my questions, and for sharing your knowledge. Your support has been invaluable and this work would not have been the same without it. I would also like to thank my examiner Alexander Hollberg for the valuable feedback and input throughout the work. This thesis marks the end of my years at Chalmers. I am grateful for everything I have learned and for all the people I have met along the way.

Olivia Carlsson, Gothenburg, June 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

BBR	Boverket's Building Regulations
EF	Emission Factor
EPD	Environmental Product Declaration
GWP	Global Warming Potential
IGU	Insulating Glass Unit
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PBL	Planning and Building Act
RSL	Reference Service Life
RSP	Reference Study Period

Contents

List of Figures

List of Tables

1
Introduction

1.1 Background

Increased concentrations of greenhouse gases in the atmosphere from human activity are creating higher average temperatures around the world (IPCC, 2018). Effects on both natural and societal systems have already been observed which stresses the need for rapid emission reductions. In 2015 the Paris agreement was adopted where world leaders committed to limiting the average global temperature increase to below 2 °C with efforts to restrict it to 1.5 °C (Swedish Climate Policy Council, 2024). However IPCC (2018) indicates that crossing 1.5 °C results in a high risk of reaching tipping points where the impacts become severe and potentially irreversible. To limit the warming to 1.5 °C greenhouse gas emissions must decrease by 45% by 2030 compared to 2010 levels and reach zero net emissions by 2050. At the same time the world's population is expected to increase from 7.6 billion people to 9.8 billion in 2050 (United Nations, 2025). This creates a clear challenge for achieving the climate targets as rapid and substantial emissions reductions must be made while meeting residential needs and providing essential infrastructure for a growing population (Li et al., 2025).

The construction sector is the largest contributor to global warming accounting for 37% of the world's total greenhouse gas emissions (United Nations Environment Programme, 2023). According to Li et al. (2025) the construction sector alone will consume the entire carbon budget for the 1.5 °C and 2 °C targets within the next two decades if current trends continue. Despite the urgent need to decarbonize the sector the progress remains insufficient and is far from aligning with the Paris agreement (United Nations Environment Programme, 2023). Most emission reduction efforts have primarily focused on reducing operational emissions which accounted for 75% of the building sector's total emissions in 2021. In contrast strategies to reduce embodied emissions have received relatively little attention as they historically have accounted for a smaller share of buildings' total emissions. However embodied emissions are expected to rise to 49% of the construction sector's total emissions by 2050. In Sweden this shift has already occurred as embodied carbon accounts for almost 50% of the sector's emissions (One Click LCA, 2025). This stresses the need to increase measures that address embodied emissions as these will account for much of the sector's emissions in the future.

Reusing building components offers significant potential to reduce embodied emissions and resource consumption by avoiding emissions associated with raw material extraction and component manufacturing (United Nations Environment Programme, 2023). Despite this potential material flows in the construction sector remain largely linear and reuse is still implemented at a very limited scale. Windows have been identified as one of the building products with significant potential for reuse (Business Region Göteborg, 2025). However, Lasvaux et al. (2025) states that the feasibility of reusing windows to lower the environmental impact of the construction sector requires further investigation as they are part of the building envelope and therefore influence the operational energy use of the building. This is commonly investigated through Life Cycle Assessment (LCA) but how to model reused products in LCA has been discussed in the literature in recent years without reaching a clear consensus (De Wolf et al., 2020). The modeling of reused components therefore remains inconsistent between studies since no commonly established framework currently exists which reduces the reliability of the results and makes comparisons between studies difficult.

Additionally, Kumar et al. (2025) notes that the highest potential for reducing a building's carbon footprint is during the early design phases. Decisions during this phase must therefore be supported by information on how different choices influence the building's environmental impact throughout its life cycle. However, conducting an LCA in early design stages is difficult due to the limited data available on the reused product and the complexity of the method. At this stage the design is not yet fixed and many alternatives have to be compared, which makes a full LCA too time-consuming and data-intensive to be practical. A simplified method is therefore needed that can estimate the climate impact from the limited information available in early design, so that different alternatives can be compared quickly. This creates a research gap regarding how the potential climate benefits of reusing windows can be modeled in a way that is suitable for early design decision-making.

1.1.1 Aim and research questions

This thesis aims to develop a simplified LCA-based method to quantify and compare the global warming potential of reused and newly manufactured windows under conditions of limited data availability for the reuse option. The method is intended to support early-stage design decisions by enabling rapid comparisons between alternatives and identifying the option with the lowest climate impact.

The following research questions are addressed:

- How can an LCA-based calculation model be structured to estimate the potential CO_2-equivalent savings associated with choosing a reused window over a newly manufactured one?
- How should the calculation parameters be handled when there is limited data available, while still ensuring reliable results?

1.1.2 Limitations

The geographical scope is limited to Sweden which means that assumptions regarding energy systems, transport distances and construction practices reflect this context. However materials and window components could be sourced from other countries. The environmental assessment is limited to the impact category global warming potential (GWP) and does not consider other environmental impact categories. Economic and social aspects of circular economy practices are also outside the study's scope.

2

Theory

2.1 Life cycle assessment (LCA)

Life cycle assessment (LCA) is a method used to calculate the environmental impact of a product or service over its entire life cycle (Miljögiraff, n.d.). The international standards ISO 14040 and ISO 14044 together form the basis for how an LCA should be conducted. ISO 14040 describes the basic framework and the parts that an LCA should contain, while ISO 14044 specifies the more detailed requirements and guidelines for how these parts are carried out. In short, ISO 14040 describes what should be included in the analysis and ISO 14044 describes how the analysis should be conducted. According to the standards, an LCA should consist of four phases: goal and scope, life cycle inventory (LCI), impact assessment (LCIA), and interpretation (see Figure 2.1).

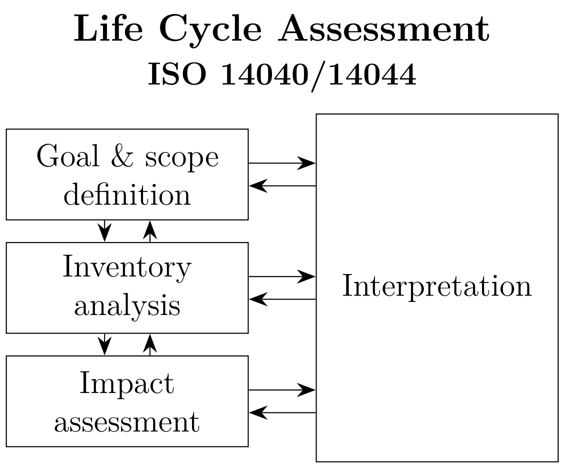

Figure 2.1: The four phases of an LCA according to ISO 14040 and ISO 14044. Adapted from Miljögiraff (n.d.).

In addition to the general standards that define the overall methodological framework for an LCA, there are also more specific standards adapted to certain sectors and product categories within a region (Ecochain, n.d.). These standards are developed in accordance with the general frameworks but specify how the methodology should be applied in the relevant context. EN 15978 and EN 15804 are the European standards that specify the guidelines and calculation methods to be applied in life cycle assessments of buildings and construction products. The standards have also been adopted as Swedish standards and are therefore referred to as SS-EN 15978 and SS-EN 15804 in Sweden (Boverket, 2018). They build on the same overall LCA principles and apply a modular structure to calculate and report the environmental impact of a building or a construction product (Gerhardsson et al., 2020). This is done by dividing the life cycle into defined modules, where each module includes the processes that are relevant for quantifying the environmental impact within the respective life cycle stage. According to the standards, the construction life cycle includes the product stage (A1–A3), the construction stage (A4–A5), the use stage (B1–B7), and the end-of-life stage (C1–C4). The standards also include an additional module, module D, which accounts for impacts beyond the product or building life cycle.

Table 2.1: Life cycle modules according to EN 15978 and EN 15804.

Production stage			Construction stage		Use stage							End of life stage				Beyond life cycle
Raw material supply	Transport to manufacturing	Manufacturing	Transport to construction site	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction	Transport	Waste processing	Disposal	Reuse, recovery, recycling potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D

For modules A–C the standards applies the cut-off allocation principle, while module D is calculated using system expansion to report potential effects outside the system boundary (Gerhardsson et al., 2020). The standards use attributional LCA to model modules A–C, while consequential LCA is used to model module D. Since the standards use different LCA approaches, the results from A–C cannot be added to the result from D and they should therefore be reported separately.

2.2 Methodological choices when modeling reuse

The modeling of climate impact from reused building components is complex since the same component is used across multiple building life cycles (De Wolf et al., 2020). Two central methodological questions in reuse are therefore which allocation method should be used to distribute the climate impact between the buildings (De Wolf et al., 2020) and where the system boundary should be drawn to determine each building's responsibility for the various reuse processes (Gerhardsson et al., 2020).

The reuse supply chain typically consists of dismantling, transport, storage, reconditioning, adaption and installation (Frossard et al., 2023). However, which activities that are required varies from case to case and depends on what is needed to return the component to a usable condition and location. How these activities are allocated between the donor and receiving building's life cycle is not explicitly regulated in EN1̃5978 (Gerhardsson et al., 2020). This is instead a subject to interpretation as the system boundary between the two building systems is established at the point of where the end-of-waste status of the component is reached. This means that the activities needed to bring the component to end-of-waste status are allocated to the donor building, while activities needed to bring it to functional equivalence to a new product thereafter are allocated to the receiving building (Ciroth & Hamed, 2025).

Gerhardsson et al. (2020) define end-of-waste as the point at which the component reaches its lowest economic value, which occurs after dismantling. This means that dismantling is allocated to the donor building while all subsequent activities in the reuse supply chain are allocated to the receiving building. However, as highlighted by Lasvaux et al. (2025), this boundary is not consistently applied across studies or guidelines and in their own assessment they choose to include dismantling within the receiving building's system boundaries. Frossard et al. (2023) argue that which building that gets the impact of dismantling depends on whether a waste audit has been conducted prior to deconstruction as this determines whether the component can be classified as waste. If a waste audit qualifies the component as reusable, it is never classified as waste and all activities including dismantling are attributed to the receiving building's life cycle. If no audit has been conducted and a standard deconstruction is carried out, the component is classified as waste and the burdens of deconstruction are excluded from the receiving building's scope.

Another important methodological choice concerns which allocation method is applied to distribute the climate impact between the buildings in which the component is used. (De Wolf et al., 2020) show that the choice of allocation method has a large influence on the result which means that results from different studies cannot be reliably compared if different methods have been used. The climate impact from reuse occurring within the studied building's life cycle is modelled in EN1̃5978 within modules A–C while reuse connected to another building's life cycle is modelled in module D (Gerhardsson et al., 2020). For modules A–C the cut-off allocation method is applied which allocates the climate impact to the life cycle in which it occurs. This is the most common allocation method for modelling the climate impact of reused products and is advantageous as it is consistent with existing LCA data and standards (Lasvaux et al., 2025), while also providing reliable results by allocating environmental impact to the life cycle in which the processes actually occurs (De Wolf et al., 2020). This means that no assumptions need to be made about the product's future life cycles, which is advantageous since the number of future reuse cycles is difficult to predict for building components with long service lives. The method also addresses the practical challenge that in a second life cycle there is often a lack of drawings and detailed information about the component's original manufacturing and material composition. By limiting the calculation to the processes that actually occur within the studied life cycle, the uncertainties that arise when attempting to distribute burdens and credits over time are thereby avoided.

Whether cut-off is the best allocation method for modelling reuse is however debated and no consensus has been reached on which method should be used (De Wolf et al., 2020). The disadvantage of the cut-off method is that it favours the building that receives reused products over the one that makes them available (Gerhardsson et al., 2020). This is because the receiving building gains the full climate benefit of avoiding manufacturing impacts while the supplying building is only credited with avoided waste management (De Wolf et al., 2020). This means that the method creates uneven incentives between design with upstream reuse and design for downstream reuse. Design with upstream reuse refers to reusing already existing products in new buildings, while design for downstream reuse refers to designing products so that they can easily be reused in future buildings. As a result of these limitations, alternative allocation methods have been developed. De Wolf et al. (2020) compare the six most common methods and how they distribute climate impact from production and end-of-life between life cycles, see Table 2.2. In the table, n denotes the total number of life cycles in which the component is used, l_c the time the component is used in the current life cycle and l_e the component's expected total lifespan. Common to these methods is that they to varying degrees allocate production impacts (A1–A3) and end-of-life impacts (C1–C4) to life cycles other than those in which they actually occur. This means that the methods rely on assumptions about the number of future life cycles, how the product will ultimately be handled and access to data about the product's original manufacturing, which can be difficult to trace for building components that have already been used for a long time.

Table 2.2: Overview of allocation methods for environmental impacts of reused building components across life cycles. Adapted from De Wolf et al. (2020).

	Initial Life Cycle				Intermediate Life Cycles				Last Life Cycle			
Method	A1–3	A4–5	B1–5	C1–4	A1–3	A4–5	B1–5	C1–4	A1–3	A4–5	B1–5	C1–4
Cut-off	✓	✓	✓	–	–	✓	✓	–	–	✓	✓	✓
End-of-life	–	✓	✓	–	–	✓	✓	–	✓	✓	✓	✓
Distributed	$\frac{1}{n}$	✓	✓	$\frac{1}{n}$	$\frac{1}{n}$	✓	✓	$\frac{1}{n}$	$\frac{1}{n}$	✓	✓	$\frac{1}{n}$
EC EF	$\frac{1}{2}$	✓	✓	$\frac{1}{2}$	–	✓	✓	–	$\frac{1}{2}$	✓	✓	$\frac{1}{2}$
Degressive	$\frac{1}{n}$	✓	✓	$\frac{1}{2}$	$\frac{1}{n}$	✓	✓	$\frac{1}{2}$	$\frac{1}{n}$	✓	✓	$\frac{1}{2}$
SIA 2032	$\frac{l_c}{l_e}$	✓	✓	$\frac{l_c}{l_e}$	$\frac{l_c}{l_e}$	✓	✓	$\frac{l_c}{l_e}$	$\frac{l_c}{l_e}$	✓	✓	$\frac{l_c}{l_e}$

n = number of life cycles, l_c/l_e = ratio of actual to expected lifespan,
✓ = allocated to the life cycle where it occurs, – = not included.

To promote reuse in the building sector, the allocation method needs to support both the use of existing products and design for future reuse as these are mutually dependent. A sufficient supply of reused products on the market is a prerequisite for them to be used in new buildings, and demand is in turn a prerequisite for actors to choose to make products available for reuse (Gerhardsson et al., 2020; Lasvaux et al., 2025). Without incentives for both types of reuse, the reuse market therefore risks not reaching its full potential. De Wolf et al. (2020) shows that none of the existing methods fully satisfies both of these requirements while also providing reliable results, meaning that the choice of allocation method involves a trade-off between reliability and the creation of incentives. However, material passports and BIM records are developing and enabling better traceability of building products' origin and climate impact. As this data becomes more accessible, alternative allocation methods have the potential to become more reliable in the future and therefore more appropriate as they create incentives for both upstream and downstream reuse. But as access to data for older building products is currently limited, the cut-off method remains the most reliable choice for modelling the climate impact of reused components today.

2.3 Reuse of windows

Windows have been identified as one of the building products with significant potential for reuse in a circular construction sector (Business Region Göteborg, 2025). However, windows are complex products with several performance requirements which can make reuse more challenging. A study by Ericsson et al. (2024) examining Swedish clients' perspectives on the reuse of building materials found that uncertainty regarding the performance of reused components is a significant barrier. Many clients reported difficulties assessing reused components due to missing documentation, product declarations, and certification, which makes it difficult to determine whether the components meets the requirements. This uncertainty particularly affects windows, which are often avoided due to concerns about thermal performance.

The thermal performance of a window is of particular importance as windows form part of the building envelope and therefore directly influence the building's thermal performance. According to the Planning and Building Act (PBL) are a construction product only allowed to be used in a building if it is suitable for its intended purpose (Sveriges riksdag, 2010). A building product is considered suitable if its properties do not jeopardize the building's ability to meet essential technical requirements and if it complies with the regulations issued by Boverket. These essential technical requirements include energy performance and thermal insulation, which are regulated in Boverket's Building Regulations (BBR) through requirements for the building's primary energy number EP_{Pet} and average thermal transmittance of the building envelope U_m (Boverket, 2024a) as shown in Table 2.3. However, the requirements vary depending on the building type and do not apply to buildings used less than four months per year, buildings without a need for heating for most of the year and buildings where no space is heated to more than 10 degrees.

Table 2.3: Maximum permitted primary energy number (EP_{pet}) and average thermal transmittance of the building envelope (U_m) by building type in BBR (Boverket, 2024a).

Building type	EP_{pet} [kWh/m^2 · year]	U_m [W/m^{2}K]
Residential		
Single-family house >130 m^2 A_{temp}	90	0.30
Single-family house 90–130 m^2 A_{temp}	95	0.30
Single-family house 50–90 m^2 A_{temp}	100	0.30
Single-family house ≤50 m^2 A_{temp}	No req.	0.33
Multi-family house	75	0.40
Non-residential		
Premises >50 m^2 A_{temp}	70	0.50
Premises ≤50 m^2 A_{temp}	No req.	0.33

BBR does not set specific requirements for the U-value of windows, but a window with poor thermal insulation may not be allowed if it prevents the building from meeting its energy requirements (Boverket, 2024a). Since energy requirements vary between building types the same window may be acceptable in one building but not in another. Other requirements however apply when windows are installed as part of alterations to an existing building. In such cases, the buildings energy performance must not decrease to the point where it longer meets its energy requirements, unless there are exceptional reasons. If the building does not meet the requirements after the alteration, a U-value of $1.2\tilde{W}$/m²K for windows should be aimed for. For the reuse of windows, this means that the thermal performance of the reused window must always be assessed in relation to the energy requirements of the receiving building. In new construction, the window must not prevent the building from meeting its energy requirements. In alterations to existing buildings, the reused window must not have a higher U-value than the window it replaces if this causes the building to no longer meet the energy requirements. If the reused window however has a lower U-value than the window it replaces, the alteration is permitted even if the building does not meet the energy requirements.

Windows are therefore rarely reused in their original form since refurbishment are often needed to achieve sufficient thermal performance (Lasvaux et al., 2025). Refurbishment is defined as

> *"Modification of an object that is waste or a product to increase or restore its performance and/or functionality or to meet applicable technical standards or regulatory requirements, with the result of making a fully functional product to be used for a purpose that is at least the one that was originally intended ."(Nasr et al., 2018)*

This makes it possible to keep parts of the original window and reduce the embodied emissions while improving its energy performance and therefore also lowering the operational emissions (Lasvaux et al., 2025). The most common window type in swedens building stock according to Boverket's BeTSI study conducted in 2007–2008 is wooden coupled windows, see Appendix D. These have a high U-value of 2.8–3.0 W/m^{2}K and several measures exist to improve their thermal performance (Energimyndigheten, 2025a). The most significant improvement is obtained by replacing the existing inner pane with a double-glazed unit with soft-coated low-emissivity glass and argon filling that reduces the U-value to 1.3 W/m^{2}K. Other measures include replacing the inner pane with a 4 mm hard-coated low-emissivity glass that reduces the U-value to 1.8 W/m^{2}K, or adding an interior 4 mm low-emissivity pane that gives a U-value of 1.4 W/m^{2}K. Both sashes can also be replaced with a fixed double-glazed unit with low-emissivity glass and argon filling that reduces the U-value to 1.4 W/m^{2}K.

3 Methodology

This chapter presents the methodology used to quantify and compare the global warming potential of the reused and the new window. The method was developed through a case study of a coupled wooden window, which was used to build and refine the LCA-based calculation framework in an iterative process. A sensitivity analysis was then carried out to determine how each parameter affects the result, and thereby which parameters must be specified by the user and which can be assigned default values. A contribution analysis was also performed to identify which processes dominate the embodied impact of the reused window.

3.1 Case study

This study is conducted as a comparative LCA where the climate savings are assessed from the demand side, since the aim is to develop a method for quantifying how much could be saved by choosing a reused product over a new one.

3.1.1 Goal

The goal of this study is to quantify and compare the climate impact of a reused window and a newly manufactured window. The LCA is conducted as part of the broader thesis aim of developing a simplified method for estimating the potential climate savings from window reuse in the early design phase and serves as the means through which the method is developed and tested. The intended application is to inform early-stage design decisions in building projects where reuse is considered as an alternative to new window. The intended audience consists of practitioners in early-phase building design such as architects and sustainability consultants as well as researchers working on LCA methodology for reused construction products.

3.1.2 Scope

The assessment is carried out at two levels. The product-level assessment quantifies the embodied climate impact of the reused window and the new reference window. The building-level assessment compares two scenarios: one in which a reused window is used in a building and one in which a new window is used.

Functional unit, referens study period (RSP) and reference service life (RSL)

The functional unit in this study is defined as 1 m^2 of window. The RSP is set to 50 years in accordance with the reference period used for buildings in Swedish LCA practice (Boverket, 2024b). The reference service life (RSL) of the new reference window is 50 years according to its EPD. The same RSL is applied to the reused window, since the RSL of reused components is difficult to establish as it depends on previous and future maintenance practices, material quality and in-use conditions (Switala-Elmhurst & Udo-Inyang, 2014). The same approach is taken by Lasvaux et al. (2025) who applies equal service life between reused and new components, and by Switala-Elmhurst & Udo-Inyang (2014) who assigns refurbished wooden windows the same RSL as in their new condition. This simplification is tested in the sensitivity analysis to evaluate how the calculated savings respond to a shorter RSL of the reused window and whether the RSL needs to be specified accurately to obtain reliable results.

Reused window

The reused window assesd in this study is a coupled wooden window from the 1960s with the dimensions of 1440 × 1340 mm, which after modifications is assumed to have a U-value of 1.3 W/m²K (Energimyndigheten, 2025a). The window is based on a typical construction used in Swedish residential buildings from this period as described by Björk et al. (2009). This window was chosen as the case study window as coupled wooden windows are the most common window type in Sweden's residential stock according to Boverkets BETSI study (Boverket, 2015b). The construction period 1960s was chosen as many houses in the Swedish residential stock were built during this decade (Björk et al., 2009). Although construction rates were higher in the 1970s, coupled wooden windows were no longer commonly produced at that time which makes the 1960s the most relevant period for the study. The design of the reused window is shown in Figure 3.1.

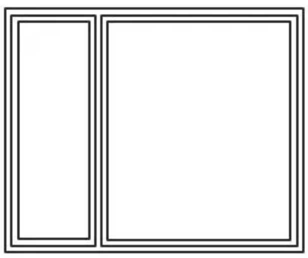

Figure 3.1: The reused window. Own illustration based on Björk et al. (2009).

New window

The window used as the new window in this study is the Elitfönster Harmoni 3-glass side-hung window with dimensions of 1230 × 1480 mm. It is a wooden window with external aluminium cladding and a triple-glazed insulating glass unit with a U-value of 1.2 W/m^{2}K. The new window was not selected to match the material composition of the reused window. This is because the supply of reused products is often limited, which restricts the designer's ability to freely choose which reused window to use (Lasvaux et al., 2025). The new window that would otherwise have been selected could therefore have a different material composition than the reused window. The design of the new window is shown in Figure 3.2.

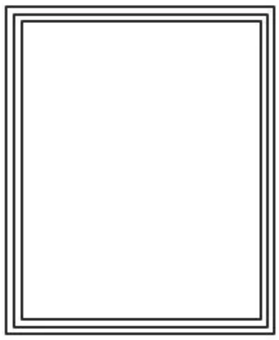

Figure 3.2: The new reference window, Elitfönster Harmoni 3-glass. Own illustration based on Elitfönster (2023).

System boundaries

The geographical scope of the study is set to Sweden, since the windows assessed are part of the Swedish building stock and the results are intended to support reuse decisions in a Swedish context.

The included life cycle modules in this study are shown in Table 3.1. Modules A1–A4 and C4 are included to capture the differences in embodied impact between the reused and the new window. Modules B4 and B6 are included because the reused and the new window may differ in RSL and U-value, which affects the number of replacements needed over the building's service life and the operational energy use. In the case study the RSL of both windows is equal to the RSP, so no replacements occur. Module B4 is however still included in the assessment so that the method remains applicable to cases where the windows differ in RSL.

Table 3.1: Life cycle modules according to EN 15978. Modules marked with x are included in this study.

Production stage			Construction stage		Use stage							End of life stage			
Raw material supply	Transport to manufacturing	Manufacturing	Transport to construction site	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction	Transport	Waste processing	Disposal
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
x	x	x	x					x		x					x

Installation (A5), dismantling (C1), transport to waste facility (C2) and sorting (C3) are assumed to be identical for both systems and are therefore not included, as they do not contribute to the difference in the comparative assessment. Emissions during use (B1) and operational water use (B7) are excluded as windows neither emit greenhouse gases nor consume water during operation. Maintenance (B2), repair (B3) and refurbishment (B5) are excluded as their impact depends on future assumptions that cannot be reliably established in the early design phase. This is consistent with common practice, as Pomponi & Moncaster (2016) found that maintenance and replacement are rarely considered in academic studies and De Wolf et al. (2017) showed that use-stage embodied carbon is often omitted in practice due to uncertainty and limited data. These modules are however likely to differ between the two systems since they have different materials that degrade at different rates which is a limitation of this study.

The product systems for both the reused and the new window are illustrated in Figure 3.3. The reused window are assumed to be selectively dismantled, since conventional demolition typically damages the window and makes reuse impossible. Selective dismantling implies that the window has been identified as reusable before removal, which means that the component retains its product status throughout the process and is not classified as waste. Since the system boundary between the donor and receiving building is set at the end-of-waste status, the dismantling activity is allocated to the receiving building's life cycle.

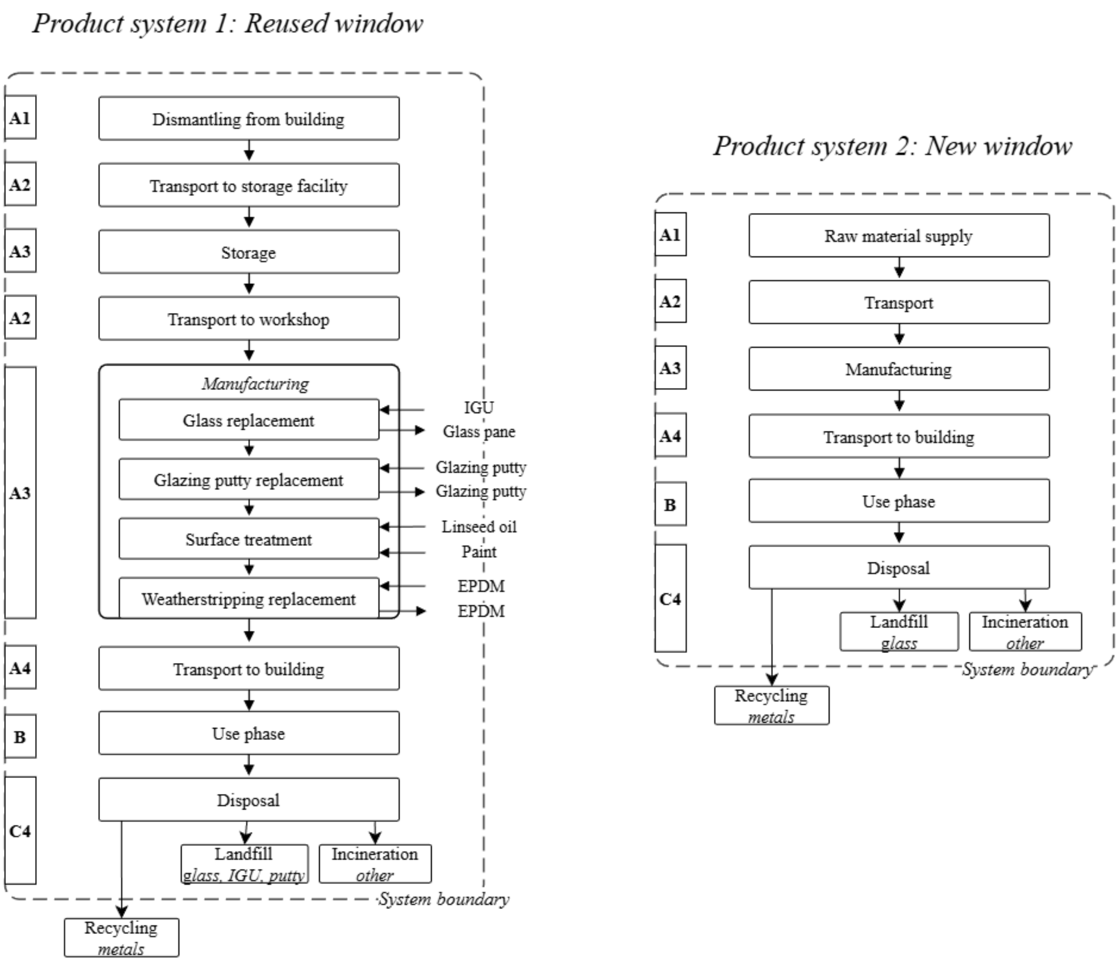

Figure 3.3: System boundaries of the two product systems.

Impact categories and impact assessment method

The life cycle impact assessment follows the Environmental Footprint (EF 3.0) method, selected to ensure consistency with emission factors from EPDs compliant with EN 15804+A2, which mandates EF 3.0 characterisation factors (EPD International, 2023). The assessment is limited to the impact category climate change, as this is the focus of the study due to the construction sector's large contribution to greenhouse gas emissions. The indicator used is GWP-fossil, expressed in kg CO_2-eq over a 100-year time horizon. This indicator was selected to ensure methodological consistency between the two product systems when using the cut-off allocation method. Under the cut-off approach the environmental burdens from the original production are not allocated to the reused window, while the new window includes its full life cycle. Including GWP-biogenic would therefore credit the new window for biogenic uptake during biomass growth without giving the same credit to the reused window. This would create a methodological inconsistency, as the new window would be assigned both -1 at production and +1 at end-of-life, while the reused window would only be assigned +1 at end-of-life. This would lead to an unfair comparison as the reused window would get higher total emissions since it is not credited for the biogenic uptake but only the release.

Type of LCA and allocation method

This study uses an attributional LCA approach in accordance with EN 15978 (Gerhardsson et al., 2020). The cut-off allocation method is applied, which assigns each impact to the life cycle in which it physically occurs (De Wolf et al., 2020). The original production impact is therefore allocated to the donor building, so the assessment of the reused window does not depend on detailed data on the original manufacturing, which is often missing in a second life cycle. The method is used because it is consistent with existing standards and LCA data (Lasvaux et al., 2025), which means that data from Ecoinvent and EPDs can be used without introducing a methodological inconsistency. Whether cut-off is the most suitable method for reuse is however debated in the literature, since it creates uneven incentives between the donor and the receiving building, as discussed in Section 2.2

Data quality requirments

As no EPDs are available for old windows, data for material quantities for the reused window are calculated based on the dimensions and geometry of a 1960s window as reported in the sectional drawings by Björk et al. (2009). The calculation method is described in detail in Appendix A. Environmental data are primarily taken from product-specific EPDs compliant with EN 15804+A2:2019 and from the Ecoinvent 3.8 cut-off unit database when no EPD is available. Environmental data for transport, district heating and electricity are taken from Boverket's climate database to reflect Swedish conditions.

3.1.3 LCI and LCIA: Product Level

Module A1

The reused window is assumed to be selectively dismantled by hand and energy input for manual dismantling is assumed to be negligible compared to the other life cycle modules and is therefore set to zero. The original raw material supply and manufacturing of the reused window are not included since these burdens are allocated to the donor building's life cycle under the cut-off allocation method.

$$GWP^{A1}_{\text{reuse}} = 0 \text{ kg CO}_2\text{e/m}^2 \text{ w.} \tag{3.1}$$

For the new window module A1 instead represents raw material supply and the value is taken directly from the EPD of the reference product.

$$GWP^{A1}_{\text{new}} = 58.78 \text{ kg CO}_2\text{e/m}^2 \text{ w.} \tag{3.2}$$

Modules A2 and A4

The reused window is assumed to be dismantled from a donor building in central Gothenburg, transported to a storage facility in Hisingen, then to a workshop in

Kungälv, and finally to the recipient building in Stockholm. At the workshop, an IGU is installed which increases the window mass between the two transport stages. The mass is therefore denoted $m_{\text{reuse}}^{\text{A2}}$ in module A2 and $m_{\text{reuse}}^{\text{A4}}$ in module A4 and is derived from the window geometry in Appendix A, Section A.6. Emissions from transport are calculated using Equation 3.3 and Equation 3.4, with parameter values presented in Table 3.2.

$$GWP_{\text{reuse}}^{A2} = EF_{\text{fuel}} \cdot E_{\text{truck},s} \cdot m_{\text{reuse}}^{A2} \cdot (d_{\text{storage}} + d_{\text{workshop}}) \tag{3.3}$$

$$GWP_{\text{reuse}}^{A4} = EF_{\text{fuel}} \cdot E_{\text{truck},l} \cdot m_{\text{reuse}}^{A4} \cdot d_{\text{site,reuse}} \tag{3.4}$$

The new reference window is assumed to be transported from Elitfönster's factory in Vetlanda to the building in Stockholm. Module A2 emissions are taken directly from the EPD, while module A4 is calculated explicitly using Equation 3.6 to reflect the project-specific transport distance.

$$GWP_{\text{new}}^{A2} = 6.52\ \text{kg}\ \text{CO}_2\text{e/m}^2 \tag{3.5}$$

$$GWP_{\text{new}}^{A4} = EF_{\text{fuel}} \cdot E_{\text{truck},l} \cdot m_{\text{new}} \cdot d_{\text{site,new}} \tag{3.6}$$

Road transport by truck is assumed as the transportation mode since the window is reused within Sweden. Generic data for energy consumption are taken from Boverket which provides values for freight transport of building components under typical Swedish conditions. These values are divided into long-distance and local distribution transport to account for differences in operating conditions, and include empty return trips. Diesel was assumed as the fuel used in the trucks as it is the dominant fuel used in road freight transport in Sweden Trafikanalys (2026). In 2026, it accounted for approximately 85.2% of the fuel used in light-duty trucks and about 93% of the fuel used in heavy-duty trucks. In Sweden, diesel of environmental class 1 (MK1) is the main diesel quality used in road transport Drivkraft Sverige (2024) and was therefore used in the calculation. In addition, suppliers of diesel in Sweden must reduce greenhouse gas emissions by 10% by blending diesel with biofuels in accordance with the reduction obligation Energimyndigheten (2024). The emission factor provided by Boverket represents diesel under the reduction obligation, meaning it includes a share of biofuels rather than purely fossil diesel.

Table 3.2: Assumed parameters and emission factors for transport modelling

Parameter	**Variable**	**Value**	**Unit**	**Source**
Distance from old building to storage	d_{storage}	10	km	Google Maps
Distance from storage to workshop	d_{workshop}	13	km	Google Maps
Distance from storage to new building	$d_{\text{site,reuse}}$	470	km	Google Maps
Distance from Vetlanda to new building	$d_{\text{site,new}}$	345	km	Google Maps
Reuse window mass	$m^{\text{A2}}_{\text{reuse}}$	0.02388	t/m^2	Calculated*
Refurbished window mass	$m^{\text{A4}}_{\text{reuse}}$	0.03274	t/m^2	Calculated*
New window mass	m_{new}	0.03882	t/m^2	EPD Elitfönster
Transport mode	–	Truck	–	Assumption
Fuel type	–	Diesel MK1	–	Assumption
Energy use, short transport	$E_{\text{truck},s}$	1.5	MJ/tonkm	Boverket
Energy use, long transport	$E_{\text{truck},l}$	1	MJ/tonkm	Boverket
Emission factor diesel MK1	EF_{fuel}	0.0899	kg CO_2e/MJ	Boverket

*See Appendix A for the calculation.

Module A3

The activities included in module A3 differ between the reused and the new reference window. For the new window module A3 represents manufacturing and its value is taken directly from the EPD. For the reused window module A3 covers storage and the modifications required to return the window to a functional condition. The total GWP of module A3 for the reused window is calculated as the sum of these two contributions using Equation 3.7. The modelling of each is described in the following sections.

$$GWP^{A3}_{\text{reuse}} = GWP^{A3,\text{store}} + GWP^{A3,\text{mod}} \tag{3.7}$$

$$GWP^{A3}_{\text{new}} = 2.65\ \text{kg}\,\text{CO}_2\text{e/m}^2\,\text{w.} \tag{3.8}$$

Storage Windows should be stored indoors in a dry and ventilated space where the temperature and humidity preferably correspond to the conditions in the building where the windows will later be installed (TMF, 2009). Storage of the window is therefore assumed to take place indoors in a ventilated and heated warehouse. The environmental impact associated with storage includes the electricity use and heating demand of the warehouse, while other potential contributions such as the construction of the warehouse and equipment are excluded from the system boundaries. The impact is allocated to the stored window based on the share of storage area it occupies and the duration of storage. The storage area occupied by a window is estimated as the window width multiplied by the frame depth, since windows should be stored upright with the bottom frame facing downward (TMF, 2009). The global warming potential from storage expressed per functional unit are calculated using Equation 3.9 and the assumed values for the parameters are presented in Table 3.3.

$$GWP^{A3,\text{store}} = \frac{(EF_{\text{el}} \cdot E_{\text{el}} + EF_{\text{heat}} \cdot E_{\text{heat}}) \cdot \cancel{b_{\text{window}}} \cdot d_{\text{frame}} \cdot t_{\text{storage}}}{\cancel{b_{\text{window}}} \cdot h_{\text{window}}} \tag{3.9}$$

Table 3.3: Assumed parameters and emission factors for storage modelling

Parameter	Variable	Value	Unit	Source
Warehouse electricity use	E_{el}	22.4	kWh/m^2/year	Sono (2024)
Warehouse heating demand	E_{heat}	31	kWh/m^2/year	Sono (2024)
Window height	h_{window}	1.34	m	Björk et al. (2009)
Frame depth	d_{frame}	0.112	m	Björk et al. (2009)
Storage time	$t_{storage}$	0.5	year	Assumption
Emission factor electricity	EF_{el}	0.037	kg CO_2e/kWh	Boverket
Emission factor district heating	EF_{heat}	0.056	kg CO_2e/kWh	Boverket

The electricity use of the warehouse was assumed to be 22.4 kWh/m^2 per year and the heating demand 31 kWh/m^2 per year, based on data from a modern BREEAM-SE certified warehouse in Sweden Sono (2024). These values may be lower than those of other facilities but are used as no other data could be found. Emission factors for electricity and district heating were obtained from Boverket's Climate Database, using the values for *Electricity, Swedish mix* and *District heating, Swedish average* to reclect swedish concicitions.

Modifications The impacts from the window modifications are calculated from the flow of each material added and removed together with their corresponding emission factors using Equation 3.10.

$$GWP^{A3,\text{mod}} = \sum_i q_i \cdot EF_i^{A1\text{-}A3} + \sum_j q_j \cdot EF_j^{C4} \tag{3.10}$$

where q_i is the flow of material i added to the process, $EF_i^{A1\text{-}A3}$ is its production emission factor, q_j is the flow of material j removed, and EF_j^{C4} is the emission factor for its disposal route.

Since this case study considers a coupled wooden window, the materials included in the assessment are based on the typical measures required for this window type, and the emissions are calculated using Equation 3.11.

$$GWP^{A3,mod} = \begin{bmatrix} q_{\text{IGU}} \\ q_{\text{putty}} \\ q_{\text{oil}} \\ q_{\text{paint}} \\ q_{\text{EPDM}} \end{bmatrix} \cdot \begin{bmatrix} EF_{\text{IGU}}^{A1\text{-}A3} \\ EF_{\text{putty}}^{A1\text{-}A3} \\ EF_{\text{oil}}^{A1\text{-}A3} \\ EF_{\text{paint}}^{A1\text{-}A3} \\ EF_{\text{EPDM}}^{A1\text{-}A3} \end{bmatrix} + \begin{bmatrix} q_{\text{glass}} \\ q_{\text{putty}} \\ q_{\text{EPDM}} \end{bmatrix} \cdot \begin{bmatrix} EF_{\text{glass}}^{C4} \\ EF_{\text{putty}}^{C4} \\ EF_{\text{EPDM}}^{C4} \end{bmatrix} \tag{3.11}$$

These material flows were determined based on restoration guidelines for coupled wooden windows provided by Slöjd & Byggnadsvård, a resource centre for building conservation within the Cultural Administration of Region Västra Götaland Slöjd och Byggnadsvård (2016). The restoration process includes removal and replacement of glazing putty, treatment of wood with raw linseed oil, repainting with linseed oil paint, and replacement of weatherstripping. To achieve a lower U-value, the inner pane is also replaced with a double-glazed unit, reducing the U-value to 1.3 W/m²K. Table **??** presents the parameters used in the calculation. The assumptions and calculations of the material flows are presented in Appendix A, while the datasets and EPDs used for the emission factors are reported in Appendix B.

Table 3.4: Material flows and emission factors for refurbishment modelling (A3, modifications)

Parameter	Variable	Value	Unit	Source
IGU quantity	q_{IGU}	0.709	m^2/m^2 w.	Calculated*
Putty quantity	q_{putty}	0.54	kg/m^2 w.	Calculated*
Linseed oil quantity	q_{oil}	0.15	kg/m^2 w.	Calculated*
Paint quantity	q_{paint}	0.67	kg/m^2 w.	Calculated*
EPDM quantity	q_{EPDM}	0.049	kg/m^2 w.	Calculated*
Glass quantity	q_{glass}	2.127	$m^2{\cdot}mm/m^2$ w.	Calculated*
IGU production	$EF_{IGU}^{A1\text{-}A3}$	33.5	kg CO_2e/m^2	EPD Pilkington
Putty production	$EF_{putty}^{A1\text{-}A3}$	0.59	kg CO_2e/kg	Ecoinvent
Linseed oil production	$EF_{oil}^{A1\text{-}A3}$	1.76	kg CO_2e/kg	Ecoinvent
Paint production	$EF_{paint}^{A1\text{-}A3}$	1.84	kg CO_2e/kg	EPD Flügger
EPDM production	$EF_{EPDM}^{A1\text{-}A3}$	2.77	kg CO_2e/kg	Ecoinvent
Glass landfill	EF_{glass}^{C4}	2.32×10^{-2}	kg CO_2e/m^2/mm	EPD Pilkington
Putty landfill	EF_{putty}^{C4}	1.06×10^{-2}	kg CO_2e/kg	Ecoinvent
EPDM incineration	EF_{EPDM}^{C4}	3.16	kg CO_2e/kg	Ecoinvent

*See Appendix A for the calculation.

Module C4

The impacts from the end-of-life stage are calculated from the flow of materials sent to disposal and their corresponding emission factors using Equation 3.12.

$$GWP^{C4} = \sum_j q_j \cdot EF_j^{C4} \tag{3.12}$$

where q_j is the flow of material j sent to disposal and EF_j^{C4} is the emission factor for its disposal route.

Both product systems are assumed to reach end-of-life after use which is recommended by Gerhardsson et al. (2020) to avoid underestimating climate impacts from uncertain future scenarios. For this window, the GWP is calculated using Equation 3.13. The material flows are calculated in Appendix A and the sources of the emission factors are reported in Appendix B. while the new windwo is taken from its EPD

$$GWP_{reuse}^{C4} = \begin{bmatrix} q_{wood} \\ q_{paint} \\ q_{EPDM} \\ q_{putty} \\ q_{glass} \\ q_{IGU} \end{bmatrix} \cdot \begin{bmatrix} EF_{wood}^{C4} \\ EF_{paint}^{C4} \\ EF_{EPDM}^{C4} \\ EF_{putty}^{C4} \\ EF_{glass}^{C4} \\ EF_{IGU}^{C4} \end{bmatrix} \tag{3.13}$$

$$GWP_{new}^{C4} = 3.16 \text{ kg } CO_2e/m^2 \text{ w.} \tag{3.14}$$

To ensure methodological consistency between the two product systems and to avoid favoring one option, the end-of-life treatment for the materials in the reused window follows the same disposal scenarios given in the EPD of the new reference window where metals go to recycling, glass to landfill, and all other materials to incineration. A review of EPDs from other window manufacturers showed that the same disposal routes are specified for these materials, indicating that these assumptions are common across the industry. The EPD does not specify an end-of-life treatment for glazing putty and is therefore assumed to go to landfill, as it consists mainly of calcium carbonate which is an inert mineral.

Table 3.5: Material flows and emission factors for disposal modelling (C4)

Parameter	Variable	Value	Unit	Source
Wood quantity	q_{wood}	13.24	kg/m^2 w.	Calculated*
Paint quantity	q_{paint}	0.67	kg/m^2 w.	Calculated*
EPDM quantity	q_{EPDM}	0.049	kg/m^2 w.	Calculated*
Glazing putty quantity	q_{putty}	0.54	kg/m^2 w.	Calculated*
Glass quantity	q_{glass}	2.127	m^2·mm/m^2 w.	Calculated*
IGU quantity	q_{IGU}	0.709	m^2/m^2 w.	Calculated*
Wood incineration	$EF^{\text{C4}}_{\text{wood}}$	9.22×10^{-3}	kg CO_2e/kg	Ecoinvent
Paint incineration	$EF^{\text{C4}}_{\text{paint}}$	2	kg CO_2e/kg	EPD Flügger
EPDM incineration	$EF^{\text{C4}}_{\text{EPDM}}$	3.16	kg CO_2e/kg	Ecoinvent
Glazing putty landfill	$EF^{\text{C4}}_{\text{putty}}$	1.05×10^{-2}	kg CO_2e/kg	Ecoinvent
Glass landfill	$EF^{\text{C4}}_{\text{glass}}$	2.32×10^{-2}	kg CO_2e/m^2/mm	EPD Pilkington
IGU landfill	$EF^{\text{C4}}_{\text{IGU}}$	2.43×10^{-1}	kg CO_2e/m^2	EPD Pilkington

*See Appendix A for the calculation.

3.1.4 LCI and LCIA: Building Level

The product-level assessment captures the difference in embodied emissions between a reused and a new window, but does not reflect the full climate impact of installing the window in a building. The operational energy use during the reference study period (RSP) and potential replacements within the can both differ between the two scenarios and these differences could reduce or even reverse the climate benefit of reuse. The comparison therefore requires integration of the product-level results into a building-level assessment. The climate saving at building level is calculated as the difference in total GWP between the new and the reuse scenarios:

$$\Delta GWP^{\text{building}} = GWP^{\text{building}}_{\text{new}} - GWP^{\text{building}}_{\text{reuse}} \tag{3.15}$$

where

$$GWP^{\text{building}}_{\text{reuse}} = GWP^{A1\text{-}A4,C4}_{\text{reuse}} + n_{\text{reuse}} \cdot GWP^{A1\text{-}A4,C4}_{\text{new}} + GWP^{B6}_{\text{reuse}} \tag{3.16}$$

$$GWP^{\text{building}}_{\text{new}} = GWP^{A1\text{-}A4,C4}_{\text{new}} + n_{\text{new}} \cdot GWP^{A1\text{-}A4,C4}_{\text{new}} + GWP^{B6}_{\text{new}} \tag{3.17}$$

The number of replacements over the RSP in the reuse scenario n_{reuse} and in the new scenario n_{new} are calculated as:

$$n_{\text{reuse}} = \left\lceil \frac{RSP - RSL_{\text{reuse}}}{RSL_{\text{new}}} \right\rceil, \qquad n_{\text{new}} = \left\lceil \frac{RSP - RSL_{\text{new}}}{RSL_{\text{new}}} \right\rceil \tag{3.18}$$

In both scenarios, any replacement that occurs within the RSP is assumed to be a new window of the same type as the one in the new scenario. This is because the future supply of reused windows cannot be guaranteed and applying reused replacements only in the reuse scenario would also create a bias that overestimates the climate benefits of reuse (Lasvaux et al., 2025). The same replacement scenario is therefore applied to both the reuse and the new scenarios. In this case study, the reference service life of both the reused and the new window is assumed to be 50 years, which equals the RSP. No replacements are therefore required within the study period, and $n_{\text{reuse}} = n_{\text{new}} = 0$.

Table 3.6: Parameters used for the integration of the case study results.

Parameter	Variable	Value	Unit	Source
Reference study period	RSP	50	years	Boverket
Reference service life, reuse	RSL_{reuse}	50	years	Assumed
Reference service life, new	RSL_{new}	50	years	(Elitfönster, 2023)
Embodied GWP, reuse	$GWP_{\text{reuse}}^{A1\text{-}A4,C4}$	29.32	kg CO_2e/m^2	Calculated
Embodied GWP, new	$GWP_{\text{new}}^{A1\text{-}A4,C4}$	72.31	kg CO_2e/m^2	Calculated
Operational GWP, reuse	GWP_{reuse}^{B6}	341.93	kg CO_2e/m^2	Calculated
Operational GWP, new	GWP_{new}^{B6}	315.63	kg CO_2e/m^2	Calculated

Module B6

Module B6 for both scenarios is calculated using equations 4.5 and 4.6 and covers the operational energy needed to compensate for the heat loss through the window over the reference study period (RSP). In the new scenario, any replacements are assumed to be identical new windows, so U_{new} stays the same over the RSP even if the window is replaced. In the reuse scenario, the reused window is replaced by a new window if its service life is shorter than the RSP. The U-value therefore changes during the RSP, which is accounted for in the equation by applying U_{reuse} during the period the reused window is in operation and U_{new} for the remaining period after it has been replaced. In this case study, the RSL for both scenarios is set to 50 years, which is equal to the RSP. The second term in the reuse equation therefore becomes zero and only U_{reuse} is used over the RSP.

$$GWP_{\text{reuse}}^{B6} = \frac{G_t \cdot EF_{\text{heat}}}{1000} \cdot (U_{\text{reuse}} \cdot RSL_{\text{reuse}} + U_{\text{new}} \cdot (RSP - RSL_{\text{reuse}})) \tag{3.19}$$

$$GWP_{\text{new}}^{B6} = \frac{G_t \cdot EF_{\text{heat}}}{1000} \cdot U_{\text{new}} \cdot RSP \tag{3.20}$$

The heating is assumed to come from district heating since it accounts for around 90% of the heating energy in multi-dwelling buildings in sweden (Energimyndigheten, 2025b) The refurbished window is assumed to reach a U-value of 1.3 W/m^{2}K through replacement of the inner pane with a double-glazed insulating unit (Energimyndigheten, 2025a), while the new reference window from Elitfönster has a U-value of 1.2 W/m^{2}K according to the manufacturer (Elitfönster, 2023). Together with the U-values, the annual degree-hours G_t determine the heat loss over the RSL. The degree-hours represent the integrated temperature difference between indoor and outdoor air over a year, and a Swedish average of 93 936 °C·h/year is used (Energimyndigheten, 2022). All parameter values used in the calculation are presented in Table 3.7.

Table 3.7: Assumed parameters and emission factor for operational energy use modelling.

Parameter	Variable	Value	Unit	Source
U-value reuse	U_{reuse}	1.3	W/m^2K	(Energimyndigheten, 2025a)
U-value new	U_{new}	1.2	W/m^2K	(Elitfönster, 2023)
Annual degree-hours, Swedish average	G_t	93 936	°C·h/year	(Energimyndigheten, 2022)
Reference service life, reuse	RSL_{reuse}	50	years	Assumed
Reference service life, new	RSL_{new}	50	years	(Elitfönster, 2023)
Emission factor district heating	EF_{heat}	0.056	kg CO_2e/kWh	Boverket

3.2 Sensitivity analysis

A sensitivity analysis was conducted to examine how assumptions regarding key input parameters affect the results. The aim of the analysis is to identify which parameters require accurate, case-specific data to ensure reliable results and which can be assigned default values without significantly affecting the outcome. This serves to simplify the application of the framework while maintaining the validity of the results. Seven parameters were tested, and the parameter values used in the analysis are presented in the following sections. The analysis was conducted as a one-at-a-time (OAT) sensitivity analysis, where each parameter is varied individually while the others are held constant. The transport parameters are however varied together in different combinations to capture how much each parameter affects the result depending on the values of the others. A probabilistic approach such as Monte Carlo analysis was not used, as the aim was to identify which parameters govern the result and must be specified by the user, rather than to quantify the combined uncertainty of the case study result.

3.2.1 Window mass, transportation distance and transportation energy use

A sensitivity analysis was conducted on the reused window mass, transport distance for the reuse scenario, and transport energy use. Since the emissions from transport are a product of these parameters, the effect of changing one parameter depends on the values of the others. A sensitivity analysis where only one parameter is varied at a time would therefore not capture this dependency. Instead, different combinations of m, d and E_{truck} are tested with the values presented in Table 3.8.

Table 3.8: Parameter values tested in the transport sensitivity analysis

Parameter	Variable	Values tested
Window mass	m	0.02, 0.03, 0.04 t/m^2
Transport distance	d	10, 50, 250, 500, 1000 km
Transport energy use	E_{truck}	1.0, 1.5 MJ/tonkm

The mass is varied between 0.02 and 0.04 t/m^2. The lower value is rounded down from the reuse window mass (0.023 t/m^2), which uses two thin single panes, and the upper value is set above the new window mass (0.039 t/m^2), which uses a triple-glazed IGU. The distance is varied between 10 and 1000 km and the energy use is varied between the two values provided by Boverket, 1.0 and 1.5 MJ/tonkm.

3.2.2 Reference service life of the reused window

A sensitivity analysis is performed on the reference service life of the reused window RSL_{reuse}. The RSL of the reused window influences both the embodied and the operational emissions. This is because if the RSL is lower than the RSP, the reused window needs to be replaced and the embodied emissions of a new window must be added to the reuse scenario. The operational emissions are also affected, since the replacement window is a new window which could have a different U-value.

Table 3.9: Parameter values tested in the RSL_{reuse} sensitivity analysis.

Parameter	Variable	Values tested
Reference service life, reused window	RSL_{reuse}	10, 20, 30, 40, 50 years

3.2.3 Annual degree-hours

A sensitivity analysis is performed on the annual degree-hours G_t, where four additional values are tested in addition to the Swedish national average used in the case study, which was based on Boverket's climate database. These values are taken from Energimyndigheten (2022) and are based on the four climate zones into which Sweden is divided. The counties and municipalities included in each zone are presented in Table 3.11.

Table 3.10: Parameter values tested in the annual degree-hours sensitivity analysis. The annual degree-hours are based on the normal year 1981–2010 (Energimyndigheten, 2022).

Climate zone	National mean	Zone 1	Zone 2	Zone 3	Zone 4
G_t (Kh)	93 936	129 984	107 400	92 184	80 568

Table 3.11: Geographical coverage of the Swedish climate zones according to Boverket (2015a).

Climate zone	Counties and municipalities
Zone I	Norrbotten, Västerbotten and Jämtland counties
Zone II	Västernorrland, Gävleborg, Dalarna and Värmland counties
Zone III	Jönköping, Kronoberg, Östergötland, Södermanland, Örebro, Västmanland, Stockholm, Uppsala and Gotland counties and Västra Götaland county excluding the municipalities Göteborg, Härryda, Mölndal, Partille and Öckerö
Zone IV	Kalmar, Blekinge, Skåne and Halland counties and the municipalities Göteborg, Härryda, Mölndal, Partille and Öckerö in Västra Götaland county

3.2.4 U-value of the reused window

A sensitivity analysis is performed on the U-value of the reused window U_{reuse}, and the tested values are presented in Table 3.12. The tested values cover the U-values that this window type can achieve through the different upgrade measures described in Section 2.3.

Table 3.12: Parameter values tested in the U_{reuse} sensitivity analysis

Parameter	Variable	Values tested
U-value, reused window	U_{reuse}	1.3, 1.4, 1.5, 1.6, 1.7, 1.8 W/m^{2}K

3.2.5 Emission factor for district heating

A sensitivity analysis is performed on the emission factor for district heating EF_{heat} to evaluate whether the results are sensitive to the local heat supply mix. The baseline value corresponds to the Swedish national average reported in Boverket's climate database, used in the case study. To represent the geographical variation in the Swedish district heating system, the analysis tests the local emission factors for six district heating networks operated by major Swedish utilities, taken from the 2024 local environmental values reported by Energiföretagen Sverige (2024). The selected networks cover the full range from low-carbon to high-carbon supply, and the tested values are presented in Table 3.13.

Table 3.13: Parameter values tested in the EF_{heat} sensitivity analysis.

Network	Utility	EF_{heat} (g CO_2e/kWh)
Swedish avg. (baseline)	—	(baseline)
Vänersborg	Vattenfall AB	1.91
Kungsbacka	Statkraft Värme AB	12.17
Göteborg	Göteborg Energi AB	47.53
Stockholm	Stockholm Exergi AB	54.96
Linköping	Tekniska Verken	109.68
Malmö/Burlöv	E.ON	143.39

3.2.6 Storage parameters

A sensitivity analysis is performed on the warehouse electricity use E_{el}, the warehouse heating demand E_{heat}, and the storage time t_{storage} to evaluate whether the default values can be applied across different storage scenarios or whether they need to be specified for each case. The baseline values for E_{el} and E_{heat} are taken from a BREEAM-SE certified warehouse (Sono, 2024), which represents a particularly energy efficient facility and is likely to underestimate the energy use of an average Swedish warehouse. Energy use statistics for Swedish warehouses could however not be found and a 100 % increase of both E_{el} and E_{heat} is therefore applied to represent a less efficient facility. The storage time is varied between 0.25 and 2 years to test the influence of longer storage periods. The tested values are presented in Table 3.14.

Table 3.14: Parameter values tested in the storage sensitivity analysis.

Parameter	**Variable**	**Tested values**
Electricity use	E_{el}	22.4 (baseline), 44.8
Heating demand	E_{heat}	31 (baseline), 62
Storage time	t_{storage}	0.25, 0.5 (baseline), 1.0, 1.5, 2.0

E_{el} and E_{heat} in kWh/m^2/year and t_{storage} in years.

4
Results and discussion

This chapter presents and discusses the results of the study. The results from the case study are presented first and used to identify which processes dominate the impact of the reused window. The sensitivity analysis then shows how each parameter affects the result, which forms the basis for the calculation guidelines of the LCA parameter framework. The chapter ends by discussing the limitations of the method and the choice of new reference window.

4.1 Results from the case study

Figure 4.1 shows the GWP per m^2 window for the two scenarios where reused windows or new windows are installed in a building. The results are split into embodied emissions and operational emissions. Adding all modules together gives a total GWP of 371.25 kg CO_2e/m^2 for the reuse scenario and 387.94 kg CO_2e/m^2 for the new scenario. Choosing reuse therefore saves 16.69 kg CO_2e/m^2 or 4.3 % compared to choosing new windows.

For the embodied emissions, the reuse scenario has a GWP of 29.32 kg CO_2e/m^2 compared to 72.31 kg CO_2e/m^2 for the new scenario. Reuse therefore saves 42.99 kg CO_2e/m^2 in embodied emissions, which is 59 % less than the embodied GWP of the new scenario. However, this saving is partly offset by the operational impact, which is 341.93 kg CO_2e/m^2 for the reuse scenario and 315.63 kg CO_2e/m^2 for the new scenario. The new scenario therefore has 26.30 kg CO_2e/m^2 lower operational impact because the reused window has a higher U-value (1.3 W/m^2K) than the new window (1.2 W/m^2K), which means more heat is lost through the window and more energy is needed for heating over the RSP. This shows that even a small difference of 0.1 W/m^2K in U-value of the two windows can significantly affect the climate benefit of reuse which is also shown in the sensitivity analysis in Section 4.3.4.

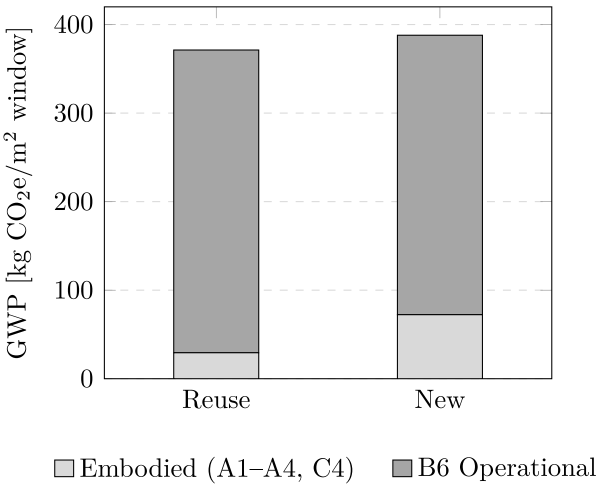

Figure 4.1: Total GWP per m^2 window for the reuse and new scenario, split into embodied and operational energy use contributions.

4.1.1 Contribution analysis of the reused case study windows embodied emissions

Table 4.1 and Figure 4.2 show the contribution of each process to the total embodied GWP of the reused window of 29.32 kg CO_2e/m^2.

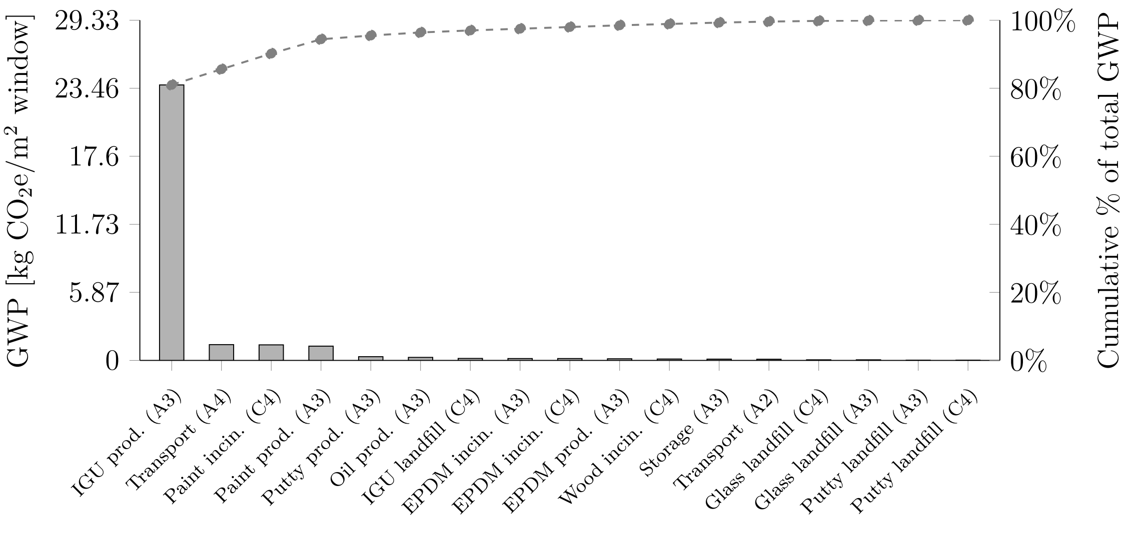

Figure 4.2: Pareto analysis of embodied GWP contributions per process for the reused window.

The IGU production is the largest single contributor at 23.75 kg CO_2e/m^2, which corresponds to approximately 81% of the embodied emissions of the reused window and around 6.4% of its total emissions. The four largest contributors are the IGU production, the transport to the building site, the paint incineration and the paint production. Together they account for over 94% of the total embodied GWP, while the remaining processes each contribute around 1% or less of the total embodied emissions. The result shows that the embodied GWP of the reused window is dominated by a small number of processes, while the majority of the included processes contribute marginally to the total.

Table 4.1: Contribution of each process to the total embodied GWP of the reused window.

Module / process	**GWP [kg CO_2e/m^2 w.]**	**% of total**
A1 Dismantling	**0.00**	**0.0%**
A2 Transport	**0.073**	**0.3%**
A3 Storage + Refurbishment	**26.02**	**88.7%**
Storage	0.11	0.4%
IGU (production)	23.75	81.0%
Paint (production)	1.23	4.2%
Glazing putty (production)	0.32	1.1%
Linseed oil (production)	0.26	0.9%
EPDM (production)	0.14	0.5%
EPDM (incineration)	0.15	0.5%
Glass pane (landfill)	0.05	0.2%
Glazing putty (landfill)	0.01	0.0%
A4 Transport to building	**1.38**	**4.7%**
C4 Disposal	**1.84**	**6.3%**
Paint (incineration)	1.34	4.6%
IGU (landfill)	0.17	0.6%
EPDM (incineration)	0.15	0.5%
Wood (incineration)	0.12	0.4%
Glass (landfill)	0.05	0.2%
Glazing putty (landfill)	0.01	0.0%
Total	**29.32**	**100.0%**

4.2 Sensitivity analysis

This section presents the results from the sensitivity analysis for the parameters assessed in this study.

4.2.1 Window mass, transportation distance and transportation energy use

The results from the sensitivity analysis presented in Table 4.2 show that the difference between $E_{\text{truck}} = 1.0$ and $E_{\text{truck}} = 1.5\,\text{MJ/tonkm}$ is below 0.1 kg CO_2e/m^2 at $d = 50\,\text{km}$. Since $E_{\text{truck}} = 1.5$ is only used for local transport distances where the absolute transport emissions are small, the effect on the result is negligible. The default value $E_{\text{truck}} = 1.0\,\text{MJ/tonkm}$ can therefore be used in all cases to simplify the framework without significantly affecting the results. The difference between the lowest and highest mass at the longest transport distance of $d = 1000\,\text{km}$ is 1.80 kg CO_2e/m^2 and the mass can therefore be assigned a default value without significantly affecting the result. The difference between the shortest and longest transport distance at the highest mass is 3.56 kg CO_2e/m^2. The transport distance therefore has a noticeable but limited influence on the result, and does not need to be specified exactly but should be estimated by the user based on the project location to obtain reliable results.

Table 4.2: Sensitivity of total GWP_{savings} (kg CO_2e/m^2) to the reuse transport parameters.

	$d = 10$ km		$d = 50$ km		$d = 250$	$d = 500$	$d = 1000$
Mass m	$E = 1.0$	$E = 1.5$	$E = 1.0$	$E = 1.5$	$E = 1.0$	$E = 1.0$	$E = 1.0$
0.02	18.13	18.12	18.06	18.02	17.70	17.25	16.35
0.03	18.12	18.11	18.02	17.95	17.48	16.80	15.45
0.04	18.11	18.10	17.97	17.88	17.25	16.35	14.55

4.2.2 Reference service life (RSL)

The results from the sensitivity analysis presented in Table 4.3 show that the savings depend entirely on the reference service life of the reused window, which must therefore be specified by the user to ensure reliable results. Positive savings are only obtained when this service life is equal to the RSP of 50 years, as this is the only case where no replacement is needed. When the service life is shorter than the RSP the reused window has to be replaced by a new window within the study period and the savings become negative. This is because the reuse scenario then includes the embodied emissions of both the reused window and the new replacement window, while the new scenario only includes the emissions of one new window. The negative savings are largest at a service life of 40 years and become smaller as the service life decreases. This happens because the new replacement window has a lower U-value than the reused window. The earlier the replacement takes place, the longer the new window is in use within the RSP. This lowers the operational energy use and partly compensates for the extra embodied emissions from the replacement.

Table 4.3: Sensitivity of total GWP_{savings} (kg CO_2e/m^2) to the reference service life of the reused window RSL_{reuse} (years).

RSL_{reuse} (years)	10	20	30	40	50
Total savings	−34.58	−39.84	−45.10	−50.36	16.69

4.2.3 Annual heating degrees

The results from the sensitivity analysis presented in Table 4.4 show that the savings depend strongly on the annual heating degree-hours. The savings range from 20.43 kg CO_2e/m^2 in the mildest climate zone to 6.60 kg CO_2e/m^2 in the coldest, which is a difference of 13.83 kg CO_2e/m^2. The difference between the climate zones is large even though the U-value difference between the two windows is only 0.1 W/m^{2}K. This shows that this parameters must be specified based on the location of the building and cannot be a fixed value.

Table 4.4: Sensitivity of total GWP_{savings} (kg CO_2e/m^2) to the annual degree-hours G_t for the four Swedish climate zones and the national average.

Climate zone	Zone 1	Zone 2	Mean	Zone 3	Zone 4
Total savings	6.60	12.92	16.69	17.18	20.43

4.2.4 U-value

The results from the sensitivity analysis of the U-value presented in Table 4.5 show that the savings depend strongly on the U-value of the reused window. The savings decrease by 26.30 kg CO_2e/m^2 for every increase of 0.1 W/m^2K in the U-value and turn negative already at a U-value of 1.4 W/m^2K. The U-value of the reused window must therefore be specified accurately by the user for the results to be reliable.

Table 4.5: Sensitivity of total $GWP_{savings}$ (kg CO_2e/m^2) to the U-value of the reused window.

U_{reuse} (W/m^2K)	1.3	1.4	1.5	1.6	1.7	1.8
Total savings	16.69	−9.61	−35.91	−62.21	−88.52	−114.82

4.2.5 Emission factor for district heating

The results from sensitivity presented in Table 4.6 show that the savings depend strongly on the emission factor of the district heating network. The savings range from 42.09 kg CO_2e/m^2 in Vänersborg to −24.36 kg CO_2e/m^2 in Malmö/Burlöv which is a difference of 66.45 kg CO_2e/m^2. The emission factor must therefore be specified based on the local district heating network and cannot be fixed as an average value to obtain reliable results.

Table 4.6: Sensitivity of total $GWP_{savings}$ (kg CO_2e/m^2) to the emission factor for district heating EF_{heat}.

Network	Vänersborg	Stockholm	Sw. avg (baseline)	Linköping	Malmö/Burlöv
EF_{heat} (g CO_2e/kWh)	1.91	54.96	56.00	109.68	143.39
Total savings	42.09	17.18	16.69	−8.52	−24.36

4.2.6 Storage parameters

The results from the sensitivity analysis presented in Table 4.7 show that the storage parameters have a marginal influence on the total savings. The savings vary between 16.74 kg CO_2e/m^2 at the shortest storage time of 0.25 years with baseline energy use and 15.94 kg CO_2e/m^2 at the longest storage time of 2 years with doubled energy use, which is a difference of 0.80 kg CO_2e/m^2. The storage parameters can therefore be assigned default values without significantly affecting the result.

Table 4.7: Sensitivity of total $GWP_{savings}$ (kg CO_2e/m^2, modules A1–A4, C4 and B6) to the storage parameters E_{el}, E_{heat} and $t_{storage}$.

$t_{storage}$ (years)	0.25	0.5	1.0	1.5	2.0
Baseline ($E_{el} = 22.4$, $E_{heat} = 31$)	16.74	16.69	16.58	16.48	16.37
Doubled ($E_{el} = 44.8$, $E_{heat} = 62$)	16.69	16.58	16.37	16.15	15.94

4.3 Calculation guidelines for the LCA framework

This section presents the calculation guidelines for the LCA parameter framework developed in this study, including the equations and parameters needed to quantify the climate savings from reuse, as well as how each parameter should be handled to obtain reliable results. The framework calculates the potential climate saving from reuse as the difference in total GWP between the new and the reuse scenarios, expressed per m^2 of window.

$$\Delta GWP = GWP_{\text{new}} - GWP_{\text{reuse}} \tag{4.1}$$

The total GWP for each scenario is the sum of the embodied emissions of the installed window, the embodied emissions of any replacement windows installed within the RSP, and the emissions from the operational energy use of the scenario.

$$GWP_{\text{reuse}} = \underbrace{GWP_{\text{reuse}}^{A1\text{-}A4,C4}}_{\text{installed window}} + \underbrace{n_{\text{reuse}} \cdot GWP_{\text{new}}^{A1\text{-}A4,C4}}_{\text{replacements (B4)}} + \underbrace{GWP_{\text{reuse}}^{B6}}_{\text{operational}} \tag{4.2}$$

$$GWP_{\text{new}} = \underbrace{GWP_{\text{new}}^{A1\text{-}A4,C4}}_{\text{installed window}} + \underbrace{n_{\text{new}} \cdot GWP_{\text{new}}^{A1\text{-}A4,C4}}_{\text{replacements (B4)}} + \underbrace{GWP_{\text{new}}^{B6}}_{\text{operational}} \tag{4.3}$$

In the framework, any replacement window installed within the RSP is assumed to be a new window, since the future supply of reused windows cannot be guaranteed. The number of replacements is calculated using Eq. 4.4 as the number of new windows needed to cover the remaining years of the RSP after the first installed window has reached the end of its service life.

$$n_{\text{reuse}} = \left\lceil \frac{RSP - RSL_{\text{reuse}}}{RSL_{\text{new}}} \right\rceil, \qquad n_{\text{new}} = \left\lceil \frac{RSP - RSL_{\text{new}}}{RSL_{\text{new}}} \right\rceil \tag{4.4}$$

The RSP is set to 50 years according to Boverket (2024b). The RSL of the new window is taken as default from the chosen reference window, while the RSL of the reused window must be specified by the user to ensure reliable results. This is however likely to be hard to establish for a user, since it depends on the condition of the window and future maintenance habits, which are usually unknown.

The emissions from the operational energy use are calculated as the heat loss through the windows for each scenario over the reference study period, multiplied by the emission factor of district heating. In the reuse scenario the reused window is in use for RSL_{reuse} years with U-value U_{reuse}, after which it is replaced by a new window with U-value U_{new} for the remaining $RSP - RSL_{\text{reuse}}$ years. In the new scenario all installed windows have the same U-value U_{new}, so the operational emissions are the same regardless of how many replacements occur within the RSP. The operational emissions for the two scenarios are calculated using Eq. 4.5 and Eq. 4.6.

$$GWP_{\text{reuse}}^{B6} = \frac{G_t \cdot EF_{\text{heat}}}{1000} \cdot (U_{\text{reuse}} \cdot RSL_{\text{reuse}} + U_{\text{new}} \cdot (RSP - RSL_{\text{reuse}})) \tag{4.5}$$

$$GWP^{B6}_{\text{new}} = \frac{G_t \cdot EF_{\text{heat}}}{1000} \cdot U_{\text{new}} \cdot RSP \tag{4.6}$$

The U-value of the new window is taken as default from the chosen reference windows EPD, while EF_{heat} and G_t are default based on the location provided by the user. The U-value of the reused window must however be specified by the user, since the sensitivity analysis showed that even a 0.1 difference in U-value had a large impact on the results. The U-value of the reused window is however hard to establish for a user, since the study by Ericsson et al. (2024) showed that the thermal performance of reused windows is usually unknown. As a result, actors today often avoid reusing windows since their performance is not verified. Reused windows made available on the reuse market should therefore be tested to enable those considering purchasing them to make a reliable assessment of their climate impact.

4.3.1 Embodied emissions of the new window

The embodied emissions for the new window are taken directly from the EPD of the new window chosen by the user for modules A1, A2, A3 and C4. The embodied emissions from module A4 are however calculated explicitly, since the transport distance from the manufacturer to the construction site is project-specific. The total GWP of the new window is calculated using Eq. 4.7.

$$GWP_{\text{new}} = GWP^{A1-A3,C4}_{\text{new}} + EF_{\text{diesel}} \cdot E_{\text{truck}} \cdot m^{A4}_{\text{new}} \cdot d^{A4}_{\text{new}} \tag{4.7}$$

The mass of the new window is taken as default from the EPD of the new window. E_{truck} is set to a default of 1 MJ/tonkm as it does not affect the results according to the sensitivity analysis. The fuel emission factor EF_{diesel} is taken as default from Boverket. This default can be used since diesel is the dominant fuel in Swedish road freight transport, accounting for about 85% of the fuel used in light-duty trucks and 93% in heavy-duty trucks Trafikanalys (2026), so it is highly likely that the transport is carried out using diesel. The transport distance should however be specified by the user based on the project location. This does however not need to be done exactly and can be an estimate while still giving reliable results, as shown in the sensitivity analysis.

4.3.2 Embodied emissions of the reused window

The framework defines the embodied emissions of the reused window for module A1 as zero, since the cut-off allocation method assigns the burdens from the original raw material supply to the donor building's life cycle. The reused window is assumed to be selectively dismantled, as conventional demolition typically damages the window and makes reuse impossible. The dismantling is therefore allocated to the receiving building, but the energy required for manual dismantling is assumed to be negligible compared to the other life cycle modules and is therefore set to zero.

$$GWP^{A1}_{\text{reuse}} = 0 \tag{4.8}$$

Modules A2 and A4 cover the transport from the donor building to the storage and manufacturing workshop (A2) and from the workshop to the construction site (A4), and are calculated using Eq. 4.9. Since the window mass can differ between the two stages depending on the refurbishment scope for that window type, a separate mass is used for each. The sensitivity analysis showed that the window mass has a limited effect on the result, so the value provided from the material quantification framework can be used in the absence of data while still giving reliable results. The EF_{diesel} and E_{truck} are set to default with the same values as for the modeling of the new windows embodied emissions. The transport distance should be specified by the user, but as for the new window this does not need to be done exactly and can be an estimate.

$$GWP^{A2,A4}_{\text{reuse}} = EF_{\text{diesel}} \cdot E_{\text{truck}}(m^{A2}_{\text{reuse}} \cdot d^{A2}_{\text{reuse}} + m^{A4}_{\text{reuse}} \cdot d^{A4}_{\text{reuse}}) \tag{4.9}$$

Module A3 covers the storage emissions and the modification emissions. As shown in the sensitivity analysis, the storage emissions remain small across the full range of tested parameters. The storage emissions are therefore assigned a default value of 0.43 kg CO_2e/m^2, which corresponds to a doubled energy use and a storage time of 1 year. The energy use was doubled since the value in the case study was based on a BREEAM certified warehouse, which has a lower energy use than a typical non-certified warehouse. A storage time of 1 year was chosen rather than a shorter period to keep the default on the conservative side, since the storage time is case dependent and a default value should not risk underestimating the emissions.

$$GWP^{A3,\text{store}}_{\text{reuse}} = 0.43 \text{ kg CO}_2\text{e/m}^2 \tag{4.10}$$

The modification emissions cover the production of new materials added to the window during refurbishment and the disposal of materials removed. The refurbishment scope must be defined separately for each window type, since the extent of the modifications and the materials needed to restore or upgrade it vary between window types. For a coupled wooden window the modification emissions are calculated using Eq. 4.11. The material flows are assumed to be hard to establish for a user, since Ericsson et al. (2024) reported that documentation for reused windows is usually missing, and there are no available EPDs for new windows of this type from which material data can be drawn. An additional framework has therefore been developed that estimates these flows based on the window geometry, which is presented in the next section.

$$\begin{aligned} GWP^{A3,\text{mod}}_{\text{reuse}} = {} & q_{\text{IGU}} \cdot EF^{A1\text{-}A3}_{\text{IGU}} + q_{\text{putty}} \cdot EF^{A1\text{-}A3}_{\text{putty}} + q_{\text{oil}} \cdot EF^{A1\text{-}A3}_{\text{oil}} \\ & + q_{\text{paint}} \cdot EF^{A1\text{-}A3}_{\text{paint}} + q_{\text{EPDM}} \cdot EF^{A1\text{-}A3}_{\text{EPDM}} \\ & + q_{\text{glass}} \cdot EF^{C4}_{\text{glass}} + q_{\text{putty}} \cdot EF^{C4}_{\text{putty}} + q_{\text{EPDM}} \cdot EF^{C4}_{\text{EPDM}} \end{aligned} \tag{4.11}$$

Module C4 covers the final disposal of the materials in the reused window at the end of its service life. The materials that are disposed of differ between window types and should therefore be defined separately. For a coupled wooden window the disposal emissions are calculated using Eq. 4.12, with material quantities taken from the window parameter framework.

$$GWP^{C4}_{\text{reuse}} = q_{\text{wood}} \cdot EF^{C4}_{\text{wood}} + q_{\text{paint}} \cdot EF^{C4}_{\text{paint}} + q_{\text{EPDM}} \cdot EF^{C4}_{\text{EPDM}} + q_{\text{putty}} \cdot EF^{C4}_{\text{putty}} + q_{\text{glass}} \cdot EF^{C4}_{\text{glass}} + q_{\text{IGU}} \cdot EF^{C4}_{\text{IGU}} \quad (4.12)$$

For other window types, the C4 emissions can instead be taken directly from an EPD of a new window of the same type as these are usually available. This is however an approximation and it is uncertain whether it gives reliable results. Lasvaux et al. (2025) note that a reused window was manufactured in the past and therefore reflects the materials and construction methods used at that time and a new window of the same type therefore may be made with different materials or in different quantities. The geometry-based quantification used in this study for deriving the material quantities was developed for coupled wooden windows and is not suited to more complex modern constructions such as aluminum and aluminum-clad windows. Whether a similar framework can be developed for other window types could however be addressed in further research.

Material quantification framework for a coupled wooden window

This section presents the material quantification framework for a coupled wooden window, which estimates the material quantities from the geometric parameters of the window in the absence of material data. The framework requires three groups of input parameters. The first describes the layout of the specific window assessed and must be provided by the user, since it differs from window to window. The second contains the cross-sectional dimensions of the window components, which vary with the construction decade and are assigned default values based on the sectional drawings in Björk et al. (2009). The third contains the material properties, which are also assigned default values. A complete list of the parameter values and the equations is given in Appendix.

Table 4.8: Window parameter framework.

Inputs					
User input parameters		*Default window parameters*		*Default material parameters*	
Parameter	Variable	Parameter	Variable	Parameter	Variable
Window width	b_{window}	Sash 1 width	$b_{\text{sash,1}}$	Glass density	ρ_{glass}
Window height	h_{window}	Sash 1 depth	$d_{\text{sash,1}}$	Pine density	ρ_{pine}
Glass width, light i	$b_{\text{glass,i}}$	Sash 2 width	$b_{\text{sash,2}}$	Putty density	ρ_{putty}
Glass height, light i	$h_{\text{glass,i}}$	Sash 2 depth	$d_{\text{sash,2}}$	Paint density	ρ_{paint}
Mullion length	L_{mullion}	Rebate width	b_{rebate}	Linseed oil density	ρ_{oil}
Transom length	L_{transom}	Rebate depth	d_{rebate}	EPDM density	ρ_{EPDM}
Mullions	n_{mullion}	Glazing rebate width	$b_{\text{rebate,g}}$	Paint coverage	C_{paint}
Transoms	n_{transom}	Glazing rebate depth	$d_{\text{rebate,g}}$	Oil coverage	C_{oil}
Horiz. bars, light i	$n_{\text{h,i}}$	Bar width	b_{bar}	Paint coats	$n_{\text{layers,paint}}$
Vert. bars, light i	$n_{\text{v,i}}$	Bar depth	d_{bar}	Oil coats	$n_{\text{layers,oil}}$
		Frame width	b_{frame}		
		Frame depth	d_{frame}		
		Mullion width	b_{mullion}		
		Mullion depth	d_{mullion}		
		Glass thickness	t_{glass}		
		Glass thickness IGU	t_{IGU}		
		Sashes with putty	$n_{\text{sash,putty}}$		
Equations					
See Appendix for the full set of equations.					
Outputs (per m^2 window)					
q_{wood}, q_{glass}, q_{putty}, q_{paint}					
q_{oil}, q_{EPDM}, q_{IGU}, $m^{\text{A2}}_{\text{reuse}}$, $m^{\text{A4}}_{\text{reuse}}$					

The reliability of the method has however not been validated by comparing the material quantities derived from the geometry-based framework against those reported in an EPD since these could not been found. A validation is however possible for coupled wooden windows, since some manufacturers today publish sectional drawings for this window type even though they do not provide EPDs. In future studies the material quantities for such a window could be calculated with the framework and compared against the actual quantities obtained from the manufacturer, which should be possible to retrieve on request. This would make it possible to assess how accurately the geometry-based method reproduces the real material use.

Although the geometry-based quantities were not validated against measured data, the contribution analysis indicates that the result is robust to uncertainty in most material inputs. The embodied impact is dominated by the IGU, which accounts for 23.92 kg CO_2e/m^2, or 81.6% of the embodied and 6.4% of the total impact. The IGU area is derived directly from the light and window dimensions, which are user inputs that are assumed to easy to obtain from the supplier and therefore subject to little uncertainty. The paint is the second largest contributor at 2.57 kg CO_2e/m^2, or 8.8% of the embodied and 0.7% of the total impact. Its quantity is more uncertain, as it depends on a large number of parameters but its low contribution limits the effect on the result. The remaining materials together account for 2.83 kg CO_2e/m^2, or 9.7% of the embodied and 0.8% of the total impact. Any uncertainty in these quantities therefore has therefore a negligible effect on the result.

4.4 Limitations of the method

The method has several limitations that affect how the results should be interpreted. The use stage modules for maintenance (B2), repair (B3) and refurbishment (B5) were excluded because their impact depends on assumptions about future events that cannot be reliably established in the early design phase. These modules are however likely to differ between the two windows, since they can consist of different materials that degrade at different rates. The savings could therefore be either over- or underestimated, depending on how the maintenance needs differ between the reused and the new window over the RSP.

The geometry-based material quantification was not validated against measured data, since no EPD or material data for a coupled wooden window could be found for comparison. The material quantities used for the reuse scenario therefore rely on the geometric assumptions of the framework. The contribution analysis shows that this has a limited effect on the result, since the embodied impact is dominated by the IGU, whose area is derived directly from user inputs that are subject to little uncertainty. The paint is the second largest contributor, but its quantity has a limited effect on the result given its small share of the total. The remaining materials each contribute around 1% or less, so uncertainty in these quantities has a negligible effect on the total.

The method is also limited to the impact category GWP and to the Swedish context. Other environmental impact categories are not considered, and a reused window that lowers the GWP may perform differently in other categories. The assumptions on energy systems, transport and disposal routes reflect Swedish conditions and would need to be adjusted before the method is applied in another context.

4.5 The choice of the new reference window

The choice of the new reference window has a large influence on the result. It determines the RSL of the new window, the U-value and the embodied emissions used in the comparison. A reference window with a lower U-value decreases the operational energy use of the new scenario. The larger the difference in U-value between the reused and the new window the larger this effect becomes. The case study shows that even a difference of 0.1 W/m^2K between the windows offsets a large part of the savings from reuse. The RSL of the reference window also affects the result, since it determines how many times the windows must be replaced within the RSP. If the reused window reaches the end of its service life while the new window does not the savings turn negative. This is because the replacement adds the embodied emissions of an additional new window to the reuse scenario only. If the new window also has an RSL shorter than the RSP both scenarios require replacements within the study period. The disadvantage of reuse is then reduced since the additional embodied emissions are no longer unique to the reuse scenario. The reference window also determines the embodied emissions used in the comparison. A reference window with higher embodied emissions increases the savings from reuse, since these emissions are avoided when a window is reused instead of produced new. The reference window must therefore be chosen to represent the new window that would otherwise have been installed instead of the reused one, as the comparison would otherwise not reflect the actual climate impact of choosing reuse over a new window.

5

Conclusion

This thesis aimed to develop a simplified LCA-based method to quantify and compare the global warming potential of reused and newly manufactured windows under limited data availability. Two research questions were addressed.

The first research question concerned how an LCA-based calculation model can be structured to estimate the CO_2-equivalent savings from choosing a reused window over a new one. The developed method calculates the saving as the difference in total GWP between using a new and reused window, expressed per m^2 of window. It includes the modules A1–A4,B4, B6 and C4. The inclusion of these modules ensures that any difference between the two windows in material quantities, reference service life or U-value is reflected in the comparison. For the reuse scenario, where material data is usually missing, a geometry-based framework was developed to estimate the material quantities of a coupled wooden window from its geometric parameters. Together these frameworks let a designer estimate the climate savings of reuse, with very little information about the window.

The second research question concerned how the parameters should be handled when data is limited while still ensuring reliable results. The sensitivity analysis showed that the result is governed by a small number of parameters that must be specified by the user, namely the U-value and the reference service life of the reused window, the emission factor of the local district heating network and the annual degree-hours. These have a large effect on the result and must therefore be provided accurately to obtain reliable results. The transport distance should also be provided by the user since it is case dependent and a single default value does not give reliable results across all cases, but it can be roughly estimated. The user must also provide a few window geometry parameters to the material quantification framework, but these can be measured directly and do not require detailed material documentation. The remaining parameters can be assigned default values without compromising the reliability of the result.

As the results depend heavily on the U-value and RSL, the main barrier to a reliable assessment is the lack of documented performance data for reused windows. The U-value and the remaining service life are usually unknown, yet both have a decisive influence on the result. Testing and documenting reused windows on the reuse market would therefore allow those considering reuse to make a reliable assessment of the climate impact and support reuse as a measure to reduce the emissions in the construction sector.

5.1 Future research

This study identifies several areas for future research. The most important is a method to determine the RSL of a reused window. The RSL has a large effect on the result but is hard to establish since it depends on the condition of the window and future maintenance. A method to assess the remaining service life of a reused window is therefore essential to obtain reliable savings estimates. The use stage modules for maintenance (B2), repair (B3) and refurbishment (B5) were excluded in this study since their impact cannot be reliably established in the early design phase. These modules are however likely to differ between the reused and the new window, as they could consist of different materials that degrade at different rates. Future research could investigate how these modules can be modeled for windows and how large their influence is on the comparison between reuse and new.

Further research could also validate the accuracy of geometry-based material quantification framework. Some manufacturers publish sectional drawings for coupled wooden windows without providing EPDs. The material quantities derived from the framework could be calculated for such a window and compared against the actual quantities obtained from the manufacturer on request. This would make it possible to assess how accurately the geometry-based method reproduces the real material use. The material quantification framework was also developed for coupled wooden windows and is not suited to more complex modern constructions such as aluminium and aluminium-clad windows. Since material data is often missing for reused windows, further research could investigate whether the C4 emissions can be approximated from EPDs for new windows of the same type while still ensuring reliable results. This approximation is uncertain, since a reused window reflects the materials and construction methods used at the time it was manufactured and may therefore differ from a new window of the same type. If the approximation turns out to give misleading results, further research could instead look into how the material quantification framework can be expanded to other window types.

Finally , the study also only defined the material flows needed during manufacturing to model the modification emissions of a coupled wooden window. The modification emissions depend on which materials are added when the window is refurbished, and these differ between window types since each type requires a different refurbishment scope. Further research could therefore investigate which material flows are needed to model the modification emissions of other window types, so that the framework can be extended to a wider part of the window stock.

Bibliography

Björk, C., Nordling, L., & Reppen, L. (2009). *Så byggdes villan: Svensk villaarkitektur från 1890 till 2010*. Formas.

Boverket. (2015a). *Boverkets föreskrifter om ändring i verkets byggregler (2011:6) – föreskrifter och allmänna råd* (BFS 2015:3). https://rinfo.boverket.se/BFS2011-6/pdf/BFS2015-3.pdf

Boverket. (2015b). *Databasen från BETSI*. https://www.boverket.se/sv/om-boverket/oppna-data/betsi-oppna-data/databasen-fran-betsi/

Boverket. (2018). *Standarder för LCA*. https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/livscykelanalys/miljodata-och-lca-verktyg/standarder-for-lca

Boverket. (2024a). *Boverkets byggregler (BBR) – föreskrifter och allmänna råd* (BFS 2024:14). https://rinfo.boverket.se/BFS2011-6/pdf/BFS2024-14.pdf

Boverket. (2024b). *Metodval för LCA*. https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/livscykelanalys/sahar-gors-en-lca/metodval-for-lca/

Business Region Göteborg. (2025). *Storskalig återbruksmarknad: Byggprodukter som kan driva omställningen* (Guide). https://www.businessregiongoteborg.se/kunskapsbank/guider/storskalig-aterbruksmarknad-byggprodukter-som-kan-driva-omstallningen

Bygma. (2024). *Tätlist P EPDM vit 9x5,5mm 24m*. Bygma Sverige AB. https://www.bygma.se/produkter/farg/tejp-skyddspapp--tackplast/tatningslist/tatlist-p-epdm-vit-9x55mm-24m/

Ciroth, A., & Hamed, A. (2025). *Module D in environmental product declarations (EPDs)* (Whitepaper, Version 2). GreenDelta GmbH. https://www.greendelta.com/wp-content/uploads/2025/01/Module-D-in-Environmental-Product-Declarations_08012025_final.pdf

Dana Lim A/S (via Vingstorp). (n.d.). *Linoljekitt – Glasmästarkitt*. https://vingstorp.com/webshop/linoljekitt-glasmastarkitt/

De Wolf, C., Pomponi, F., & Moncaster, A. (2017). Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. *Energy and Buildings, 140*, 68–80. https://doi.org/10.1016/j.enbuild.2017.01.075

De Wolf, C., Hoxha, E., & Fivet, C. (2020). Comparison of environmental assessment methods when reusing building components: A case study. *Sustainable Cities and Society, 61*, 102322. https://doi.org/10.1016/j.scs.2020.102322

Drivkraft Sverige. (2024). *Diesel.* https://drivkraftsverige.se/fakta-statistik/drivmedel/diesel/

Ecochain. (n.d.). *Explained: LCA standards.* https://helpcenter.ecochain.com/en/articles/9515835-explained-lca-standards

Elitfönster AB. (2023). *Elitfönster Harmoni 3-glass windows – ETIL-AL – Window* (EPD-IES-0004893:004). The International EPD System. https://www.environdec.com/library/epd4893

Encyclopaedia Britannica. (1998). *Putty.* https://www.britannica.com/technology/putty

Energiföretagen Sverige. (2024). *Miljövärdering av fjärrvärme.* https://www.energiforetagen.se/statistik/fjarrvarmestatistik/miljovardering-av-fjarrvarme/

Energimyndigheten. (2022). *Energistatistik för småhus 2021 – Kvalitetsdeklaration.* Statens energimyndighet. https://www.energimyndigheten.se/499cf0/globalassets/statistik/officiell-statistik/statistikprodukter/energistatistik-i-smahus/bas/rapport_02v01_smh2021_kvalitetsdeklaration.pdf

Energimyndigheten. (2024). *Reduktionsplikt.* https://www.energimyndigheten.se/klimat/transporter/reduktionsplikt/

Energimyndigheten. (2025a). *Fönster: En guide från energi- och klimatrådgivningen* (ET 2025:01). Statens energimyndighet. https://energimyndigheten.a-w2m.se/Arkitektkopia/ViewTemplate?tid=c467b3e8c3d14754a72ea9498962f83e

Energimyndigheten. (2025b). *Ny energistatistik för flerbostadshus.* Statens energimyndighet. https://www.energimyndigheten.se/nyhetsarkiv/2025/ny-energistatistik-for-flerbostadshus/

EPD International. (2023). *Environmental performance indicators.* https://www.environdec.com/services/environmental-performance-indicators/gpi-5

Ericsson, F., Mjörnell, K., & Janson, U. (2024). Reuse of building materials—the perspective of Swedish clients. *Cleaner Engineering and Technology, 23*, 100848. https://doi.org/10.1016/j.clet.2024.100848

Flügger. (n.d.). *Technical data sheet: FL WT Wind.* https://assets.flugger.dk/static/ir/875042/TDS_FL%20WT%20WIND_sv.pdf

Flügger Group A/S. (2023). *Environmental product declaration: Flügger Wood Tex Window* (EPD-IES-0011699:001). The International EPD System. https://www.environdec.com/library/epd11699

Frossard, M., Lasvaux, S., Petetin, F., & Gross, L. (2023). Reuse practices in building construction: Proposition of a life cycle assessment methodology and application to a case study in Switzerland. *Journal of Physics: Conference Series, 2600*, 152007. https://doi.org/10.1088/1742-6596/2600/15/152007

Gerhardsson, H., Andersson, J., & Thrysin, Å. (2020). *Återbrukets klimateffekter vid byggnation: Handledning för klimatberäkningar i enlighet med EN 15978* (Rapport nr C 562). IVL Svenska Miljöinstitutet. https://ccbuild.se/media/o1fgus3f/%C3%A5terbrukets-klimateffekter-vid-byggnation_-handledning.pdf

Intergovernmental Panel on Climate Change. (2018). *Summary for policymakers. Special report: Global warming of 1.5 °C*. https://www.ipcc.ch/sr15/chapter/spm/

Kumar, D., Maurya, K. K., Mandal, S. K., Mir, B. A., Nurdiawati, A., & Al-Ghamdi, S. G. (2025). Life cycle assessment in the early design phase of buildings: Strategies, tools, and future directions. *Buildings, 15*(10), 1612. https://doi.org/10.3390/buildings15101612

Lasvaux, S., Frossard, M., Demonchy, G., Müller, K., Bofinger, C., Rudolf, B., Pfäffli, K., Zea, E., Xiong, S., & Habert, G. (2025). *Reuse-LCA: Identification of the reduction potential of the environmental impacts of Swiss buildings through material reuse* (Final report). Swiss Federal Office of Energy (SFOE). https://zirkular.net/wp-content/uploads/2025/07/8169-20250331-reuse-lca-heig-vd-final-report-e-ec-vf2.pdf

Li, C., Pradhan, P., Chen, G., Kropp, J. P., & Schellnhuber, H. J. (2025). Carbon footprint of the construction sector is projected to double by 2050 globally. *Communications Earth & Environment, 6*, 831. https://doi.org/10.1038/s43247-025-02840-x

Miljögiraff. (n.d.). *Standard för livscykelanalys ISO 14040 & 14044*. https://miljogiraff.se/kunskapshubb/standard-for-livscykelanalys-iso-14040-14044/

Nasr, N., Russell, J., Bringezu, S., Hellweg, S., Hilton, B., Kreiss, C., & von Gries, N. (2018). *Redefining value – The manufacturing revolution: Remanufacturing, refurbishment, repair and direct reuse in the circular economy* (A Report of the International Resource Panel). United Nations Environment Programme. https://wedocs.unep.org/handle/20.500.11822/31612

One Click LCA. (2025). *Embodied carbon vs. operational carbon*. https://oneclicklca.com/en/resources/articles/embodied-carbon-vs-operational-carbon

Pilkington (NSG Group). (2023a). *Pilkington Insulight™ 4/16/4 double IGU with offline coated glass* (EPD-IES-0009512:001). EPD International. https://www.environdec.com/library/epd9512

Pilkington (NSG Group). (2023b). *Pilkington Optifloat™ float glass* (EPD-

IES-0008816:001). EPD International. https://www.environdec.com/library/epd8816

Pomponi, F., & Moncaster, A. (2016). Embodied carbon mitigation and reduction in the built environment – What does the evidence say? *Journal of Environmental Management, 181*, 687–700. https://doi.org/10.1016/j.jenvman.2016.08.036

Rakennuskemia. (n.d.). *Pure linseed oil (cold-pressed).* https://rakennuskemia.se/products/pure-linseed-oil-cold-pressed-pellavaoljy-kylmapuristettu

Slöjd och Byggnadsvård. (2016). *Fönsterrenovering.* https://www.slojdochbyggnadsvard.se/siteassets/sob/fonsterrenovering-2016.pdf

Sono Sverige AB. (2024). *Sonos centrallager ur ett hållbarhetsperspektiv.* https://www.sono.se/kunskap/sonos-centrallager-ur-ett-hallbarhetsperspektiv

Sveriges riksdag. (2010). *Plan- och bygglag (2010:900)* (SFS 2010:900). https://www.riksdagen.se/sv/dokument-och-lagar/dokument/svensk-forfattningssamling/plan-och-bygglag-2010900_sfs-2010-900/

Swedish Climate Policy Council. (2024). *Report of the Swedish Climate Policy Council 2024.* https://www.klimatpolitiskaradet.se/wp-content/uploads/2024/06/reportoftheswedishclimatepolicycouncil2024.pdf

Swedish Wood. (n.d.). *Swedish sawn dried timber of spruce or pine* (EPD-IES-0002537:002). https://www.environdec.com/library/epd2537

Switala-Elmhurst, K. M., & Udo-Inyang, P. D. (2014). Life cycle assessment of residential windows: Saving energy with window restoration. In *50th ASC Annual International Conference Proceedings*. Associated Schools of Construction. http://ascpro0.ascweb.org/archives/cd/2014/paper/CPRT207002014.pdf

Trä- och Möbelföretagen (TMF). (2009). *Projektering, montage, skötsel och underhåll av fönster och ytterdörrar.* https://mox.leiab.se/Media/FileLibrary/Old/TMF-Projektering_Montage_Skotsel_och_underhall.pdf

Trafikanalys. (2026). *Fordon i län och kommuner 2025.* https://www.trafa.se/globalassets/statistik/vagtrafik/fordon/2026/fordon-i-lan-och-kommuner-2025.pdf

Udi, U. J., Yussof, M. M., & Kamarudin, M. K. (2023). Environmental degradation of structural glass systems: A review of experimental research and main influencing parameters. *Ain Shams Engineering Journal, 14*, 101970. https://doi.org/10.1016/j.asej.2022.101970

United Nations. (2025). *World population projected to reach 9.8 billion in 2050.* https://www.un.org/en/desa/world-population-projected-reach-98-billion-2050-and-112-billion-2100

United Nations Environment Programme. (2023). *Building materials and the climate: Constructing a new future*. https://www.unep.org/resources/report/building-materials-and-climate-constructing-new-future

A

Calculation of the material flows used in the LCA for the reused case study window

This appendix presents the material flow calculations for the case study window. The window parameters were estimated from the sectional drawings in Björk et al. (2009) and are summarized in Table A.1. All material quantities are calculated per unit window area (per FU).

Table A.1: Window parameters for the case study window (1960).

Parameter	Variable	Value	Unit
Outer width of window	b_{window}	1.440	m
Outer height of window	h_{window}	1.340	m
Glass width light 1	$b_{\text{glass},1}$	0.240	m
Glass width light 2	$b_{\text{glass},2}$	0.900	m
Glass height light 1	$h_{\text{glass},1}$	1.200	m
Glass height light 2	$h_{\text{glass},2}$	1.200	m
Inner sash width	$b_{\text{sash},1}$	0.042	m
Inner sash depth	$d_{\text{sash},1}$	0.033	m
Outer sash width	$b_{\text{sash},2}$	0.046	m
Outer sash depth	$d_{\text{sash},2}$	0.031	m
Rebate width	b_{rebate}	0.010	m
Rebate depth	d_{rebate}	0.070	m
Glazing rebate width	$b_{\text{rebate,g}}$	0.010	m
Glazing rebate depth	$d_{\text{rebate,g}}$	0.014	m
Frame width	b_{frame}	0.045	m
Frame depth	d_{frame}	0.112	m
Mullion width	b_{mullion}	0.061	m
Mullion depth	d_{mullion}	0.112	m
Mullion length	L_{mullion}	1.340	m
Glass thickness	t_{glass}	0.003	m
IGU pane thickness	$t_{\text{glass,IGU}}$	0.004	m
Number of sashes with putty	$n_{\text{sash,putty}}$	1	–
Number of mullions	n_{mullion}	1	–
Number of transoms	n_{transom}	0	–
Horizontal glazing bars light i	$n_{\text{h,i}}$	0	–
Vertical glazing bars light i	$n_{\text{v,i}}$	0	–

A.1 Wood quantity

The wood quantity per FU is calculated as the sum of the timber volumes of the frame, mullions, transoms, glazing bars and sashes, multiplied by the pine density $\rho_{\text{pine}} = 518$ kg/m^3 (Swedish Wood, n.d.), divided by the window area, see Equation A.1. The component cross-sectional volumes are calculated separately in Sections A.1.1. The case study window has no transoms or glazing bars, but these are still included to keep the methodology applicable to other window configurations. The input parameters for the wood quantity calculation are listed in Table **??**.

$$q_{\text{wood}} = \frac{\rho_{\text{pine}} \cdot (V_{\text{frame}} + V_{\text{mullion}} + V_{\text{transom}} + V_{\text{bar}} + V_{\text{sash}})}{b_{\text{window}} \cdot h_{\text{window}}} \tag{A.1}$$

Table A.2: Input values and result for the wood quantity calculation.

Parameter	Variable	Value	Unit
Frame volume	V_{frame}	$2.413 \cdot 10^{-2}$	m^3
Mullion volume	V_{mullion}	$7.279 \cdot 10^{-3}$	m^3
Transom volume	V_{transom}	0	m^3
Glazing bar volume	V_{bar}	0	m^3
Sash volume	V_{sash}	$1.793 \cdot 10^{-2}$	m^3
Outer width of window	b_{window}	1.440	m
Outer height of window	h_{window}	1.340	m
Pine density	ρ_{pine}	518	kg/m^3
Wood quantity per FU	$\mathbf{q_{wood}}$	**13.24**	$\mathbf{kg/m^2}$

Inserting the values:

$$q_{\text{wood}} = \frac{518 \cdot (2{,}413 \cdot 10^{-2} + 7{,}279 \cdot 10^{-3} + 0 + 0 + 1{,}793 \cdot 10^{-2})}{1{,}440 \cdot 1{,}340} = 13{,}24 \text{ kg/m}^2$$

A.1.1 Wood component volume

This section presents the calculation of the volumes of the five wood components: frame, mullion, transom, glazing bars and sash.

Frame volume The frame cross-sectional volume is calculated using Equation A.2 with the input values listed in Table A.3. The rebate is a cut in the window frame where the sash sits and is therefore subtracted from the cross-sectional area to avoid overestimation of the timber volume. The frame runs along all four sides of the window and the length is therefore calculated as twice the sum of the outer window width and height.

$$V_{\text{frame}} = (b_{\text{frame}} \cdot d_{\text{frame}} - b_{\text{rebate}} \cdot d_{\text{rebate}}) \cdot 2(b_{\text{window}} + h_{\text{window}}) \tag{A.2}$$

Table A.3: Input values and result for the frame volume calculation.

Parameter	Variable	Value	Unit
Frame width	b_{frame}	0.045	m
Frame depth	d_{frame}	0.112	m
Rebate width	b_{rebate}	0.010	m
Rebate depth	d_{rebate}	0.070	m
Outer width of window	b_{window}	1.440	m
Outer height of window	h_{window}	1.340	m
Frame volume	$\mathbf{V_{frame}}$	$\mathbf{2.413 \cdot 10^{-2}}$	$\mathbf{m^3}$

Inserting the values:

$$V_{\text{frame}} = (0{,}045 \cdot 0{,}112 - 0{,}010 \cdot 0{,}070) \cdot 2(1{,}440 + 1{,}340) = 2{,}413 \cdot 10^{-2} \text{ m}^3$$

Mullion volume The mullion cross-sectional volume is calculated using Equation A.3 with the input values listed in Table A.4. Since the mullion separates two lights it has a rebate on each side, and two rebate areas are therefore subtracted from the cross-sectional area. The mullion runs vertically between the lights and the length is therefore equal to the outer height of the window.

$$V_{\text{mullion}} = (b_{\text{mullion}} \cdot d_{\text{mullion}} - 2 \cdot b_{\text{rebate}} \cdot d_{\text{rebate}}) \cdot n_{\text{mullion}} \cdot L_{\text{mullion}} \tag{A.3}$$

Table A.4: Input values and result for the mullion volume calculation.

Parameter	Variable	Value	Unit
Mullion width	b_{mullion}	0.061	m
Mullion depth	d_{mullion}	0.112	m
Rebate width	b_{rebate}	0.010	m
Rebate depth	d_{rebate}	0.070	m
Number of mullions	n_{mullion}	1	–
Mullion length	L_{mullion}	1.340	m
Mullion volume	$\mathbf{V_{mullion}}$	$\mathbf{7.279 \cdot 10^{-3}}$	$\mathbf{m^3}$

Inserting the values:

$$V_{\text{mullion}} = (0{,}061 \cdot 0{,}112 - 2 \cdot 0{,}010 \cdot 0{,}070) \cdot 1 \cdot 1{,}340 = 7{,}279 \cdot 10^{-3} \text{ m}^3$$

Transform volume The transom cross-sectional volume is calculated using Equation A.4. Transoms have the same cross-sectional area as mullions but differ in length and orientation.

$$V_{\text{transom}} = (b_{\text{mullion}} \cdot d_{\text{mullion}} - 2 \cdot b_{\text{rebate}} \cdot d_{\text{rebate}}) \cdot n_{\text{transom}} \cdot L_{\text{transom}} \tag{A.4}$$

The case study window has no transoms, so $n_{\text{transom}} = 0$ and therefore $V_{\text{transom}} = 0$ m^3.

Glazing bar volume The glazing bar volume is calculated using Equation A.5. Each bar separates two glass panes and carries a glazing rebate on both sides.

$$V_{\text{bar}} = (b_{\text{bar}} \cdot d_{\text{bar}} - 2 \cdot b_{\text{rebate,g}} \cdot d_{\text{rebate,g}}) \sum_{i=1}^{n_{\text{light}}} (n_{\text{h,i}} \cdot b_{\text{glass,i}} + n_{\text{v,i}} \cdot h_{\text{glass,i}}) \tag{A.5}$$

The case study window has no glazing bars, so $n_{\text{h,i}} = n_{\text{v,i}} = 0$ and therefore $V_{\text{bar}} = 0$ m^3.

Sash volume The sash cross-sectional volume is calculated using Equation A.6 with the input values listed in Table A.5. The glazing rebate is a cut in the sash where the glass sits and is therefore subtracted from the cross-sectional area. The sash runs around all four sides of each light and the length is therefore calculated as twice the sum of the glass width and height. The window has an inner and an outer sash, summed via the bracketed cross-section.

$$V_{\text{sash}} = (b_{\text{sash,1}} \cdot d_{\text{sash,1}} + b_{\text{sash,2}} \cdot d_{\text{sash,2}} - 2 \cdot b_{\text{rebate,g}} \cdot d_{\text{rebate,g}}) \sum_{i=1}^{n_{\text{light}}} 2(b_{\text{glass,i}} + h_{\text{glass,i}}) \quad \text{(A.6)}$$

Table A.5: Input values and result for the sash volume calculation.

Parameter	**Variable**	**Value**	**Unit**
Inner sash width	$b_{\text{sash,1}}$	0.042	m
Inner sash depth	$d_{\text{sash,1}}$	0.033	m
Outer sash width	$b_{\text{sash,2}}$	0.046	m
Outer sash depth	$d_{\text{sash,2}}$	0.031	m
Glazing rebate width	$b_{\text{rebate,g}}$	0.010	m
Glazing rebate depth	$d_{\text{rebate,g}}$	0.014	m
Glass width light 1	$b_{\text{glass,1}}$	0.240	m
Glass width light 2	$b_{\text{glass,2}}$	0.900	m
Glass height light 1	$h_{\text{glass,1}}$	1.200	m
Glass height light 2	$h_{\text{glass,2}}$	1.200	m
Sash volume	$\mathbf{V_{sash}}$	$\mathbf{1.793 \cdot 10^{-2}}$	$\mathbf{m^3}$

Inserting the values:

$$\begin{aligned} V_{\text{sash}} = (&0{,}042 \cdot 0{,}033 + 0{,}046 \cdot 0{,}031 - 2 \cdot 0{,}010 \cdot 0{,}014) \\ &\cdot \left[2(0{,}240 + 1{,}200) + 2(0{,}900 + 1{,}200)\right] \\ &= 1{,}793 \cdot 10^{-2}\ \text{m}^3 \end{aligned}$$

A.2 Replaced and remaining glass quantity

During refurbishment the glass in the inner sash is removed and disposed of. The disposal emission factor is reported per m^2 of glass per millimetre of thickness which means that the material flow must be expressed as a volume. The disposed volume per FU is calculated using Equation A.7 as the sum of all light areas multiplied by the inner glass thickness, divided by the window area. The same volume remains in the window as the glass in the outer sash has the same thickness and dimensions as the glass in the inner sash.

$$q_{\text{glass}} = \frac{t_{\text{glass}} \cdot \sum_{i=1}^{n_{\text{light}}} b_{\text{glass,i}} \cdot h_{\text{glass,i}}}{b_{\text{window}} \cdot h_{\text{window}}} \quad \text{(A.7)}$$

Table A.6: Input values and result for the volume of replaced glass calculation.

Parameter	Variable	Value	Unit
Glass width light 1	$b_{\text{glass,1}}$	0.240	m
Glass width light 2	$b_{\text{glass,2}}$	0.900	m
Glass height light 1	$h_{\text{glass,1}}$	1.200	m
Glass height light 2	$h_{\text{glass,2}}$	1.200	m
Glass thickness	t_{glass}	0.003	m
Outer width of window	b_{window}	1.440	m
Outer height of window	h_{window}	1.340	m
Glass quantity per FU	$\mathbf{q_{glass}}$	$\mathbf{2.127 \cdot 10^{-3}}$	$\mathbf{m^3/m^2}$

Inserting the values:

$$q_{\text{glass}} = \frac{0{,}003 \cdot (0{,}240 \cdot 1{,}200 + 0{,}900 \cdot 1{,}200)}{1{,}440 \cdot 1{,}340} = 2{,}127 \cdot 10^{-3}\ \text{m}^3/\text{m}^2$$

A.3 IGU quantity

During refurbishment the inner pane is replaced with a double-glazed insulating glass unit (IGU). It is assumed to be Pilkington Insulight™ 4/16/4. The emission factor is reported per m^2 of IGU which means that the material flow must be expressed as an area. The installed area per FU is calculated using Equation A.8 as the sum of all light areas divided by the window area.

$$q_{\text{IGU}} = \frac{\sum_{i=1}^{n_{\text{light}}} b_{\text{glass,i}} \cdot h_{\text{glass,i}}}{b_{\text{window}} \cdot h_{\text{window}}} \tag{A.8}$$

Table A.7: Input values and result for the IGU area calculation.

Parameter	Variable	Value	Unit
Glass width light 1	$b_{\text{glass,1}}$	0.240	m
Glass width light 2	$b_{\text{glass,2}}$	0.900	m
Glass height light 1	$h_{\text{glass,1}}$	1.200	m
Glass height light 2	$h_{\text{glass,2}}$	1.200	m
Outer width of window	b_{window}	1.440	m
Outer height of window	h_{window}	1.340	m
IGU area per FU	$\mathbf{q_{IGU}}$	**0.709**	$\mathbf{m^2/m^2}$

Inserting the values:

$$q_{\text{IGU}} = \frac{0{,}240 \cdot 1{,}200 + 0{,}900 \cdot 1{,}200}{1{,}440 \cdot 1{,}340} = 0{,}709\ \text{m}^2/\text{m}^2$$

A.4 Glazing putty quantity

The putty is applied in the glazing rebate to fix and seal the glass panes and has a triangular cross-sectional area, running along the perimeter of each light and both sides of every glazing bar. The sectional drawings in Björk et al. (2009) show that putty was applied in both the inner and outer sash for windows produced before 1950, and only in the outer sash from 1950 onwards. The parameter $n_{\text{sash,putty}}$ denotes the number of sashes sealed with putty and takes the value 2 before 1950 and 1 from 1950 onwards. The putty is assumed to have a density of 2100 kg/m^3 (Dana Lim, n.d.). The quantity per FU is calculated using Equation A.9 with the input values listed in Table A.8.

$$q_{\text{putty}} = \frac{\rho_{\text{putty}} \cdot n_{\text{sash,putty}} \cdot \frac{b_{\text{rebate,g}} \cdot d_{\text{rebate,g}}}{2} \cdot \sum_{i=1}^{n_{\text{light}}} \left[2(b_{\text{glass,i}} + h_{\text{glass,i}}) + n_{\text{h,i}} \cdot b_{\text{glass,i}} + n_{\text{v,i}} \cdot h_{\text{glass,i}}\right]}{b_{\text{window}} \cdot h_{\text{window}}} \tag{A.9}$$

Table A.8: Input values and result for the glazing putty quantity calculation.

Parameter	Variable	Value	Unit
Glazing rebate width	$b_{\text{rebate,g}}$	0.010	m
Glazing rebate depth	$d_{\text{rebate,g}}$	0.014	m
Glass width light 1	$b_{\text{glass,1}}$	0.240	m
Glass width light 2	$b_{\text{glass,2}}$	0.900	m
Glass height light 1	$h_{\text{glass,1}}$	1.200	m
Glass height light 2	$h_{\text{glass,2}}$	1.200	m
Number of sashes with putty	$n_{\text{sash,putty}}$	1	–
Horizontal glazing bars light i	$n_{\text{h,i}}$	0	–
Vertical glazing bars light i	$n_{\text{v,i}}$	0	–
Putty density	ρ_{putty}	2100	kg/m^3
Outer width of window	b_{window}	1.440	m
Outer height of window	h_{window}	1.340	m
Putty quantity per FU	$\mathbf{q_{putty}}$	**0.54**	**kg/m^2**

Inserting the values:

$$q_{\text{putty}} = \frac{2100 \cdot 1 \cdot \frac{0{,}010 \cdot 0{,}014}{2} \cdot \Big[2(0{,}240 + 1{,}200) + 2(0{,}900 + 1{,}200)\Big]}{1{,}440 \cdot 1{,}340} = 0{,}54 \text{ kg/m}^2$$

A.5 Paint and linseed oil quantities

The paint and linseed oil quantities per FU are calculated using Equation A.10 and Equation A.11 with the input values listed in Table A.9. Both are applied to all exposed timber surfaces of the window. The paint is assumed to be Flügger Wood Tex Window and the paint properties are taken from its product data which reports a coverage of 8 m^2/L and a density of 1.19 kg/L (Flügger, n.d.). The linseed oil properties are taken from the manufacturer Rakennuskemia, which reports a coverage of 250 ml per 2.5–5 m^2 and a density of 0.93 kg/L (Rakennuskemia, n.d.). The mean coverage value is used, corresponding to 0.07 l/m^2. The area is calculated for each component in Section A.4.1.

$$q_{\text{paint}} = \frac{\rho_{\text{paint}} \cdot \frac{n_{\text{layers,paint}}}{C_{\text{paint}}} \cdot (A_{\text{sash}} + A_{\text{frame}} + A_{\text{mullion}} + A_{\text{transom}} + A_{\text{bar}})}{b_{\text{window}} \cdot h_{\text{window}}} \tag{A.10}$$

$$q_{\text{oil}} = \frac{(A_{\text{sash}} + A_{\text{frame}} + A_{\text{mullion}} + A_{\text{transom}} + A_{\text{bar}}) \cdot n_{\text{layers,oil}} \cdot C_{\text{oil}} \cdot \rho_{\text{oil}}}{b_{\text{window}} \cdot h_{\text{window}}} \tag{A.11}$$

Table A.9: Input values and results for the paint and linseed oil quantity calculations.

Parameter	**Variable**	**Value**	**Unit**
Sash area	A_{sash}	2.15	m^2
Frame area	A_{frame}	1.75	m^2
Mullion area	A_{mullion}	0.46	m^2
Transom area	A_{transom}	0	m^2
Glazing bar area	A_{bar}	0	m^2
Paint coverage	C_{paint}	8	m^2/l
Paint density	ρ_{paint}	1.19	kg/l
Number of paint layers	$n_{\text{layers,paint}}$	2	–
Linseed oil coverage	C_{oil}	0.07	l/m^2
Linseed oil density	ρ_{oil}	0.93	kg/l
Number of oil layers	$n_{\text{layers,oil}}$	1	–
Outer width of window	b_{window}	1.440	m
Outer height of window	h_{window}	1.340	m
Paint quantity per FU	$\mathbf{q_{paint}}$	**0.67**	$\mathbf{kg/m^2}$
Linseed oil quantity per FU	$\mathbf{q_{oil}}$	**0.15**	$\mathbf{kg/m^2}$

Inserting the values:

$$q_{\text{paint}} = \frac{1{,}19 \cdot \frac{2}{8} \cdot (2{,}15 + 1{,}75 + 0{,}46 + 0 + 0)}{1{,}440 \cdot 1{,}340} = 0{,}67\ \text{kg/m}^2$$

$$q_{\text{oil}} = \frac{(2{,}15 + 1{,}75 + 0{,}46 + 0 + 0) \cdot 1 \cdot 0{,}07 \cdot 0{,}93}{1{,}440 \cdot 1{,}340} = 0{,}15\ \text{kg/m}^2$$

A.5.1 Wood component area

Sash area The area of the sash is calculated using Equation A.12 with the input values listed in Table A.10. The cross-section perimeter is calculated as the sum of the inner and outer sash perimeters and the length as twice the sum of the glass width and height summed over the lights.

$$A_{\text{sash}} = 2(b_{\text{sash,1}} + d_{\text{sash,1}} + b_{\text{sash,2}} + d_{\text{sash,2}}) \sum_{i=1}^{n_{\text{light}}} 2(b_{\text{glass,i}} + h_{\text{glass,i}}) \tag{A.12}$$

Table A.10: Input values and result for the painted area calculation of the sash.

Parameter	Variable	Value	Unit
Inner sash width	$b_{\text{sash},1}$	0.042	m
Inner sash depth	$d_{\text{sash},1}$	0.033	m
Outer sash width	$b_{\text{sash},2}$	0.046	m
Outer sash depth	$d_{\text{sash},2}$	0.031	m
Glass width light 1	$b_{\text{glass},1}$	0.240	m
Glass width light 2	$b_{\text{glass},2}$	0.900	m
Glass height light 1	$h_{\text{glass},1}$	1.200	m
Glass height light 2	$h_{\text{glass},2}$	1.200	m
Painted sash area	$\mathbf{A_{sash}}$	**2.15**	$\mathbf{m^2}$

Inserting the values:

$$A_{\text{sash}} = 2(0{,}042 + 0{,}033 + 0{,}046 + 0{,}031) \cdot \Big[2(0{,}240 + 1{,}200) + 2(0{,}900 + 1{,}200)\Big] = 2{,}15 \text{ m}^2$$

Frame area The area of the frame is calculated using Equation A.13 with the input values listed in Table A.11. The perimeter of the frame cross-section is multiplied by twice the sum of the outer window width and height.

$$A_{\text{frame}} = 2(b_{\text{frame}} + d_{\text{frame}}) \cdot 2(b_{\text{window}} + h_{\text{window}}) \tag{A.13}$$

Table A.11: Input values and result for the painted area calculation of the frame.

Parameter	Variable	Value	Unit
Frame width	b_{frame}	0.045	m
Frame depth	d_{frame}	0.112	m
Outer width of window	b_{window}	1.440	m
Outer height of window	h_{window}	1.340	m
Painted frame area	$\mathbf{A_{frame}}$	**1.75**	$\mathbf{m^2}$

Inserting the values:

$$A_{\text{frame}} = 2(0{,}045 + 0{,}112) \cdot 2(1{,}440 + 1{,}340) = 1{,}75 \text{ m}^2$$

Mullion area The area of the mullion is calculated using Equation A.14 with the input values listed in Table A.12. The perimeter of the mullion cross-section is multiplied by the mullion length and the number of mullions.

$$A_{\text{mullion}} = 2(b_{\text{mullion}} + d_{\text{mullion}}) \cdot n_{\text{mullion}} \cdot L_{\text{mullion}} \tag{A.14}$$

Table A.12: Input values and result for the painted area calculation of the mullion.

Parameter	Variable	Value	Unit
Mullion width	b_{mullion}	0.061	m
Mullion depth	d_{mullion}	0.112	m
Number of mullions	n_{mullion}	1	–
Mullion length	L_{mullion}	1.340	m
Painted mullion area	$\mathbf{A_{mullion}}$	**0.46**	$\mathbf{m^2}$

Inserting the values:

$$A_{\text{mullion}} = 2(0{,}061 + 0{,}112) \cdot 1 \cdot 1{,}340 = 0{,}46 \text{ m}^2$$

Transform area The area of the transom is calculated using Equation A.15. Transoms have the same cross-section as mullions but differ in length and orientation.

$$A_{\text{transom}} = 2(b_{\text{mullion}} + d_{\text{mullion}}) \cdot n_{\text{transom}} \cdot L_{\text{transom}} \tag{A.15}$$

The case study window has no transoms, so $n_{\text{transom}} = 0$ and therefore $A_{\text{transom}} = 0$ m^2.

Glazing bar area The area of the glazing bars is calculated using Equation A.16. Each bar runs across one light, so the total length is the sum of the bar lengths over all lights.

$$A_{\text{bar}} = 2(b_{\text{bar}} + d_{\text{bar}}) \sum_{i=1}^{n_{\text{light}}} (n_{\text{h,i}} \cdot b_{\text{glass,i}} + n_{\text{v,i}} \cdot h_{\text{glass,i}}) \tag{A.16}$$

The case study window has no glazing bars, so $n_{\text{h,i}} = n_{\text{v,i}} = 0$ and therefore $A_{\text{bar}} = 0$ m^2.

A.6 EPDM weatherstripping quantity

Weatherstripping is replaced during refurbishment to prevent air leakage between the sash and the frame. It is assumed to be a self-adhesive EPDM P-profile strip with a linear density of $\rho_{\text{EPDM}} = 0{,}0133$ kg/m (Bygma, 2024). The weatherstripping is placed around all inner sashes, so the total length is the sum of the perimeters of the lights. The quantity per FU is calculated using Equation A.17 with the input values listed in Table A.13.

$$q_{\text{EPDM}} = \frac{\rho_{\text{EPDM}} \cdot \sum_{i=1}^{n_{\text{light}}} 2(b_{\text{glass,i}} + h_{\text{glass,i}})}{b_{\text{window}} \cdot h_{\text{window}}} \tag{A.17}$$

Table A.13: Input values and result for the EPDM weatherstripping quantity calculation.

Parameter	Variable	Value	Unit
Glass width light 1	$b_{\text{glass,1}}$	0.240	m
Glass width light 2	$b_{\text{glass,2}}$	0.900	m
Glass height light 1	$h_{\text{glass,1}}$	1.200	m
Glass height light 2	$h_{\text{glass,2}}$	1.200	m
EPDM linear density	ρ_{EPDM}	0.0133	kg/m
Outer width of window	b_{window}	1.440	m
Outer height of window	h_{window}	1.340	m
EPDM quantity per FU	$\mathbf{q_{EPDM}}$	**0.049**	**kg/m^2**

Inserting the values:

$$q_{\text{EPDM}} = \frac{0{,}0133 \cdot \left[2(0{,}240 + 1{,}200) + 2(0{,}900 + 1{,}200)\right]}{1{,}440 \cdot 1{,}340} = 0{,}049 \text{ kg/m}^2$$

A.7 Total window mass for transportation

The total window mass per FU is used to model the transportation of the window in modules A2 and A4. The mass is calculated before and after refurbishment to capture the change in glass mass when the inner pane is replaced with an IGU. Only wood and glass are included, since these dominate the total mass of the window. The contributions of glazing putty, paint, linseed oil and weatherstripping are small in comparison and are therefore omitted from the total mass used for the transportation modelling. Before refurbishment the window contains two plain glass panes of $t_{\text{glass}} =$ 3 mm (Björk et al., 2009), one in each sash. After refurbishment the inner plain pane is replaced with an IGU consisting of two 4 mm panes (**?**), so the window contains the outer plain pane ($t_{\text{glass}} = 3$ mm) and the two IGU panes ($t_{\text{glass,IGU}} = 4$ mm each). The glass density is assumed to be 2500 kg/m^3 (Udi et al., 2023). The total window mass before and after refurbishment is calculated using Equation C.20 and Equation C.21 with the input values listed in Table A.14.

$$m_{\text{reuse}}^{\text{A2}} = q_{\text{wood}} + \frac{\rho_{\text{glass}} \cdot 2t_{\text{glass}} \cdot \sum_{i=1}^{n_{\text{light}}} b_{\text{glass,i}} \cdot h_{\text{glass,i}}}{b_{\text{window}} \cdot h_{\text{window}}} \tag{A.18}$$

$$m_{\text{reuse}}^{\text{A4}} = q_{\text{wood}} + \frac{\rho_{\text{glass}} \cdot \left(t_{\text{glass}} + 2t_{\text{glass,IGU}}\right) \cdot \sum_{i=1}^{n_{\text{light}}} b_{\text{glass,i}} \cdot h_{\text{glass,i}}}{b_{\text{window}} \cdot h_{\text{window}}} \tag{A.19}$$

Table A.14: Input values and results for the total window mass calculation.

Parameter	Variable	Value	Unit
Glass width light 1	$b_{\text{glass},1}$	0.240	m
Glass width light 2	$b_{\text{glass},2}$	0.900	m
Glass height light 1	$h_{\text{glass},1}$	1.200	m
Glass height light 2	$h_{\text{glass},2}$	1.200	m
Glass thickness, plain	t_{glass}	0.003	m
Glass thickness, IGU pane	$t_{\text{glass,IGU}}$	0.004	m
Glass density	ρ_{glass}	2500	kg/m^3
Wood quantity	q_{wood}	13.24	kg/m^2
Outer width of window	b_{window}	1.440	m
Outer height of window	h_{window}	1.340	m
Total mass, A2 (reuse)	$\mathbf{m}_{\text{reuse}}^{\text{A2}}$	**23.88**	$\mathbf{kg/m^2}$
Total mass, A4 (refurb.)	$\mathbf{m}_{\text{reuse}}^{\text{A4}}$	**32.74**	$\mathbf{kg/m^2}$

Inserting the values:

$$m_{\text{reuse}}^{\text{A2}} = 13{,}24 + \frac{2500 \cdot 2 \cdot 0{,}003 \cdot (0{,}240 \cdot 1{,}200 + 0{,}900 \cdot 1{,}200)}{1{,}440 \cdot 1{,}340} = 23{,}88 \text{ kg/m}^2$$

$$m_{\text{reuse}}^{\text{A4}} = 13{,}24 + \frac{2500 \cdot (0{,}003 + 2 \cdot 0{,}004) \cdot (0{,}240 \cdot 1{,}200 + 0{,}900 \cdot 1{,}200)}{1{,}440 \cdot 1{,}340} = 32{,}74 \text{ kg/m}^2$$

A.8 Summary

Table A.15: Summary of the calculated material quantities and window mass

Parameter	Parameter	Value	Unit
Wood quantity per FU	q_{wood}	13.24	kg/m^2
Glass quantity per FU	q_{glass}	$2.127 \cdot 10^{-3}$	m^3/m^2
IGU area per FU	q_{IGU}	0.709	m^2/m^2
Putty quantity per FU	q_{putty}	0.54	kg/m^2
Paint quantity per FU	q_{paint}	0.67	kg/m^2
Linseed oil quantity per FU	q_{oil}	0.15	kg/m^2
EPDM quantity per FU	q_{EPDM}	0.049	kg/m^2
Total mass, A2	$m_{\text{reuse}}^{\text{A2}}$	23.88	kg/m^2
Total mass, A4	$m_{\text{reuse}}^{\text{A4}}$	32.74	kg/m^2

B
Emission factors

Material flow	**Source**	**EF**	**Unit**
EPD			
IGU production	Pilkington Insulight™ 4/16/4, S-P-09512	33.5	kg CO_2e/m^2
IGU disposal	Pilkington Insulight™ 4/16/4, S-P-09512	$2.43 \cdot 10^{-1}$	kg CO_2e/m^2
Plain glass disposal	Pilkington Optifloat™, S-P-08816	$2.32 \cdot 10^{-2}$	kg CO_2e/m^2/mm
Paint production	Flügger Wood Tex Window, EPD-IES-0011699	1.84	kg CO_2e/kg
Paint disposal	Flügger Wood Tex Window, EPD-IES-0011699	2	kg CO_2e/kg
Ecoinvent			
Glazing putty production	Calculated*	0.59	kg CO_2e/kg
	market for calcium carbonate, precipitated | calcium carbonate, precipitated | Cutoff, U – RER	0.38	kg CO_2e/kg
	market for vegetable oil, refined | vegetable oil, refined | Cutoff, U – GLO	1.76	kg CO_2e/kg
Linseed oil production	market for vegetable oil, refined | vegetable oil, refined | Cutoff, U – GLO	1.76	kg CO_2e/kg
Glazing putty disposal	treatment of inert waste, sanitary landfill | inert waste | Cutoff, U – Europe without Switzerland	$1.05 \cdot 10^{-2}$	kg CO_2e/kg
EPDM production	market for synthetic rubber | synthetic rubber | Cutoff, U – GLO	2.77	kg CO_2e/kg
EPDM disposal	treatment of waste rubber, unspecified, municipal incineration | waste rubber, unspecified | Cutoff, U – Europe without Switzerland	3.16	kg CO_2e/kg
Wood disposal	treatment of waste wood, untreated, municipal incineration | waste wood, untreated | Cutoff, U – CH	$9.22 \cdot 10^{-3}$	kg CO_2e/kg
Boverket's Climate Database			
Diesel MK1	Diesel, environmental class 1 (incl. reduction obligation)	0.0899	kg CO_2e/MJ
Electricity	Electricity, Swedish mix	0.037	kg CO_2e/kWh
District heating	District heating, Swedish average	0.056	kg CO_2e/kWh

*Calculated as a mass-weighted average of calcium carbonate (85%) and linseed oil (15%) since glazing putty typically consists of 85–90% calcium carbonate and 10–15% linseed oil (Encyclopaedia Britannica, 1998).

Table B.1: Emission factors used in the LCA, grouped by source.

C

Window framework equations and parameters

Input parameters and default values

This section lists the user input parameters (Table C.1), default values for coupled wooden windows from 1940, 1950 and 1960 (Table C.2), and material properties used in the framework (Table C.3).

Table C.1: User input parameters for the window parameter framework.

Parameter	**Variable**	**Value**	**Unit**	**Source**
Window width	b_{window}	–	m	User input
Window height	h_{window}	–	m	User input
Glass width, light i	$b_{\text{glass},i}$	–	m	User input
Glass height, light i	$h_{\text{glass},i}$	–	m	User input
Mullion length	L_{mullion}	–	m	User input
Transom length	L_{transom}	–	m	User input
Mullions	n_{mullions}	–	–	User input
Horiz. bars, light i	$n_{\text{h},i}$	–	–	User input
Vert. bars, light i	$n_{\text{v},i}$	–	–	User input

Table C.2: Default values for coupled wooden windows from 1940, 1950 and 1960, based on cross-sectional drawings from Björk et al. (2009).

Window parameter	**Variable**	**Value**			**Unit**
		1940	**1950**	**1960**	
Inner sash width	$b_{\mathrm{sash,1}}$	0.043	0.056	0.043	m
Inner sash depth	$d_{\mathrm{sash,1}}$	0.025	0.045	0.033	m
Outer sash width	$b_{\mathrm{sash,2}}$	0.046	0.041	0.048	m
Outer sash depth	$d_{\mathrm{sash,2}}$	0.031	0.034	0.031	m
Rebate width	b_{rebate}	0.010	0.010	0.010	m
Rebate depth	d_{rebate}	0.061	0.061	0.070	m
Glazing rebate width	$b_{\mathrm{rebate,g}}$	0.010	0.010	0.010	m
Glazing rebate depth	$d_{\mathrm{rebate,g}}$	0.012	0.012	0.014	m
Glazing bar width	b_{bar}	n.d.	n.d.	n.d.	m
Glazing bar depth	d_{bar}	n.d.	n.d.	n.d.	m
Frame width	b_{frame}	0.054	0.057	0.045	m
Frame depth	d_{frame}	0.090	0.095	0.112	m
Mullion/transom width	b_{mullion}	0.054	0.067	0.061	m
Mullion/transom depth	d_{mullion}	0.090	0.095	0.112	m
Glass thickness	t_{glass}	0.003	0.003	0.003	m
Number of sashes with putty	$n_{\mathrm{sash,putty}}$	2	2	1	–

Note: Coupled wooden windows from this period typically did not have glazing bars and no default dimensions are therefore provided.

Table C.3: Material properties and assumptions used in the window parameter framework.

Parameter	**Variable**	**Value**	**Unit**	**Source**
Pine density	ρ_{pine}	518	$\mathrm{kg/m^3}$	Swedish Wood (n.d.)
Glazing putty density	ρ_{putty}	2100	$\mathrm{kg/m^3}$	Dana Lim (n.d.)
Paint coverage	C_{paint}	8	$\mathrm{m^2/l}$	Flügger (n.d.)
Paint density	ρ_{paint}	1.19	kg/l	Flügger (n.d.)
Number of paint coats	$n_{\mathrm{layers,paint}}$	2	–	Assumption
Linseed oil coverage	C_{oil}	0.07	$\mathrm{l/m^2}$	Rakennuskemia (n.d.)
Linseed oil density	ρ_{oil}	0.93	kg/l	Rakennuskemia (n.d.)
Number of oil coats	$n_{\mathrm{layers,oil}}$	1	–	Assumption
Weatherstripping density	ρ_{ws}	0.0133	kg/m	Bygma (2024)

Framework equations

Wood quantity

$$q_{\text{wood}} = \frac{\rho_{\text{pine}} \cdot (V_{\text{frame}} + V_{\text{mullion}} + V_{\text{transom}} + V_{\text{bar}} + V_{\text{sash}})}{b_{\text{window}} \cdot h_{\text{window}}} \tag{C.1}$$

where

$$V_{\text{frame}} = (b_{\text{frame}} \cdot d_{\text{frame}} - b_{\text{rebate}} \cdot d_{\text{rebate}}) \cdot 2(b_{\text{window}} + h_{\text{window}}) \tag{C.2}$$

$$V_{\text{mullion}} = (b_{\text{mullion}} \cdot d_{\text{mullion}} - 2 \cdot b_{\text{rebate}} \cdot d_{\text{rebate}}) \cdot n_{\text{mullion}} \cdot L_{\text{mullion}} \tag{C.3}$$

$$V_{\text{transom}} = (b_{\text{mullion}} \cdot d_{\text{mullion}} - 2 \cdot b_{\text{rebate}} \cdot d_{\text{rebate}}) \cdot n_{\text{transom}} \cdot L_{\text{transom}} \tag{C.4}$$

$$V_{\text{bar}} = (b_{\text{bar}} \cdot d_{\text{bar}} - 2 \cdot b_{\text{rebate,g}} \cdot d_{\text{rebate,g}}) \sum_{i=1}^{n_{\text{light}}} (n_{\text{h,i}} \cdot b_{\text{glass,i}} + n_{\text{v,i}} \cdot h_{\text{glass,i}}) \tag{C.5}$$

$$V_{\text{sash}} = (b_{\text{sash,1}} \cdot d_{\text{sash,1}} + b_{\text{sash,2}} \cdot d_{\text{sash,2}} - 2 \cdot b_{\text{rebate,g}} \cdot d_{\text{rebate,g}}) \sum_{i=1}^{n_{\text{light}}} 2(b_{\text{glass,i}} + h_{\text{glass,i}}) \tag{C.6}$$

Glass quantity

$$q_{\text{glass}} = \frac{t_{\text{glass}} \cdot \sum_{i=1}^{n_{\text{light}}} b_{\text{glass,i}} \cdot h_{\text{glass,i}}}{b_{\text{window}} \cdot h_{\text{window}}} \tag{C.7}$$

IGU quantity

$$q_{\text{IGU}} = \frac{\sum_{i=1}^{n_{\text{light}}} b_{\text{glass,i}} \cdot h_{\text{glass,i}}}{b_{\text{window}} \cdot h_{\text{window}}} \tag{C.8}$$

Glazing putty quantity

$$q_{\text{putty}} = \frac{\rho_{\text{putty}} \cdot n_{\text{sash,putty}} \cdot \frac{b_{\text{rebate,g}} \cdot d_{\text{rebate,g}}}{2} \cdot \sum_{i=1}^{n_{\text{light}}} [2(b_{\text{glass,i}} + h_{\text{glass,i}}) + n_{\text{h,i}} \cdot b_{\text{glass,i}} + n_{\text{v,i}} \cdot h_{\text{glass,i}}]}{b_{\text{window}} \cdot h_{\text{window}}} \tag{C.9}$$

Paint and linseed oil quantities

$$q_{\text{paint}} = \frac{\rho_{\text{paint}} \cdot \frac{n_{\text{layers,paint}}}{C_{\text{paint}}} \cdot (A_{\text{sash}} + A_{\text{frame}} + A_{\text{mullion}} + A_{\text{transom}} + A_{\text{bar}})}{b_{\text{window}} \cdot h_{\text{window}}} \tag{C.10}$$

$$q_{\text{oil}} = \frac{(A_{\text{sash}} + A_{\text{frame}} + A_{\text{mullion}} + A_{\text{transom}} + A_{\text{bar}}) \cdot n_{\text{layers,oil}} \cdot C_{\text{oil}} \cdot \rho_{\text{oil}}}{b_{\text{window}} \cdot h_{\text{window}}} \tag{C.11}$$

where

$$A_{\text{sash}} = 2(b_{\text{sash,1}} + d_{\text{sash,1}} + b_{\text{sash,2}} + d_{\text{sash,2}}) \sum_{i=1}^{n_{\text{light}}} 2(b_{\text{glass,i}} + h_{\text{glass,i}}) \tag{C.12}$$

$$A_{\text{frame}} = 2(b_{\text{frame}} + d_{\text{frame}}) \cdot 2(b_{\text{window}} + h_{\text{window}}) \tag{C.13}$$

$$A_{\text{mullion}} = 2(b_{\text{mullion}} + d_{\text{mullion}}) \cdot n_{\text{mullion}} \cdot L_{\text{mullion}} \tag{C.14}$$

$$A_{\text{transom}} = 2(b_{\text{mullion}} + d_{\text{mullion}}) \cdot n_{\text{transom}} \cdot L_{\text{transom}} \tag{C.15}$$

$$A_{\text{bar}} = 2(b_{\text{bar}} + d_{\text{bar}}) \sum_{i=1}^{n_{\text{light}}} (n_{\text{h,i}} \cdot b_{\text{glass,i}} + n_{\text{v,i}} \cdot h_{\text{glass,i}}) \tag{C.16}$$

EPDM weatherstripping quantity

$$q_{\text{EPDM}} = \frac{\rho_{\text{EPDM}} \cdot \sum_{i=1}^{n_{\text{light}}} 2(b_{\text{glass,i}} + h_{\text{glass,i}})}{b_{\text{window}} \cdot h_{\text{window}}} \tag{C.17}$$

Window mass before and after refurbishment

$$m_{\text{reuse}}^{\text{A2}} = q_{\text{wood}} + \frac{\rho_{\text{glass}} \cdot 2t_{\text{glass}} \cdot \sum_{i=1}^{n_{\text{light}}} b_{\text{glass,i}} \cdot h_{\text{glass,i}}}{b_{\text{window}} \cdot h_{\text{window}}} \tag{C.18}$$

$$m_{\text{reuse}}^{\text{A4}} = q_{\text{wood}} + \frac{\rho_{\text{glass}} \cdot (t_{\text{glass}} + 2t_{\text{glass,IGU}}) \cdot \sum_{i=1}^{n_{\text{light}}} b_{\text{glass,i}} \cdot h_{\text{glass,i}}}{b_{\text{window}} \cdot h_{\text{window}}} \tag{C.19}$$

Window mass before and after modifications

$$m_{\text{reuse}}^{\text{A2}} = q_{\text{wood}} + \frac{\rho_{\text{glass}} \cdot 2t_{\text{glass}} \cdot \sum_{i=1}^{n_{\text{light}}} b_{\text{glass,i}} \cdot h_{\text{glass,i}}}{b_{\text{window}} \cdot h_{\text{window}}} \tag{C.20}$$

$$m_{\text{reuse}}^{\text{A4}} = q_{\text{wood}} + \frac{\rho_{\text{glass}} \cdot (t_{\text{glass}} + 2t_{\text{glass,IGU}}) \cdot \sum_{i=1}^{n_{\text{light}}} b_{\text{glass,i}} \cdot h_{\text{glass,i}}}{b_{\text{window}} \cdot h_{\text{window}}} \tag{C.21}$$

D

Window types in the Swedish building stock

Window type	**Number of windows**
Aluminium/metal	99,856
1-glazed	4,413
2-glazed	4,573
2-glazed insulated	49,086
2-glazed insulated + 1-glazed	9,806
3-glazed	13,425
3-glazed insulated	18,553
Aluminium-clad timber windows	242,697
2-glazed	37,824
2-glazed insulated	20,908
2-glazed insulated + 1-glazed	112,778
3-glazed	16,038
3-glazed insulated	54,212
(empty)	937
PBF	439
2-glazed	220
3-glazed insulated	219
Plastic-clad timber windows	15,875
2-glazed insulated	5,682
3-glazed	8,084
3-glazed insulated	2,109
Timber windows	914,248
1-glazed	6,921
1-glazed + 3-glazed insulated	624
2-glazed	349,913
2-glazed insulated	64,528
2-glazed insulated + 1-glazed	198,912
3-glazed	105,711
3-glazed insulated	189,391

Table D.1: Number of windows by type in the Swedish building stock Boverket (2015b).

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY