Chapter 39
Illustrative Case Study: Life Cycle Assessment of Four Window Alternatives

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Abstract This report serves as an example report on how to perform an LCA according to the guidance given in Chap. 37 and how to structure the report according to the reporting template in Chap. 38. The goals of the LCA were (i) to perform a benchmarking of a prototype wood/composite (W/C) window made out of glass fibre against three alternative window types currently offered in the market (made of wood (W), wood/aluminium (W/ALU), and PVC) and (ii) to identify environmental hotspots for each window system.

39.1 Executive Summary

Nor-win, a Danish-based windows manufacturer, commissioned an LCA study with the goals (i) to perform a benchmarking of a prototype wood/composite (W/C) window made out of glass fibre against three alternative window types currently offered in the market (made of wood (W), wood/aluminium (W/ALU), and PVC) and (ii) to identify environmental hotspots for each window system. The compared windows differ regarding their ability to prevent heat from escaping the building (insulation performance).

The four window types are compared on the basis of their main function, which is allowing daylight inside the building. The functional unit is thus "Allow daylight

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into a residential building through a physical barrier, equivalent to light being transmitted through an area of 1.82 m^2 with visible light transmittance of at least 0.6, for 20 years".

System boundaries comprise all life cycle stages from cradle to grave, including transportation and provision of utilities (electricity or heat). The manufacturing technology for all four windows, including the elements composing the pane and the frame, represent the technology, which is currently used by Nor-win and its suppliers. Nor-win is the provider of primary data used in the product system model. Generic databases were used for background processes and for some foreground processes for which no primary data could be retrieved from the suppliers.

The results show that for most impact categories the impact scores follow the order W/C < W = W/ALU < PVC. The W/C window has the lowest environmental impact in all 14 impact categories, while the PVC window system has the highest impact for 10 impact categories. For nearly all the non-toxicity-related impact categories, the life cycle impacts of the four windows correspond to approximately 10% of the total annual average impacts of an average EU27 citizen in the year 2010.

The main contributor of environmental impacts is the generation of indoor heating to compensate for heat losses through the window. The contribution of this process to the total life cycle impact is for all four windows around 90% for climate change, freshwater eutrophication, or resource depletion, and above 50% for nearly all other impact categories. The manufacturing stage is relevant for impacts on stratospheric ozone depletion, and ionising radiation (human health) across all windows, for impacts on freshwater ecotoxicity and human toxicity (PVC window), and land use (W window).

Several assumptions had to be made for the modelling of the product systems. While most of them were not found to be important for our conclusions, the modelling of chromium steel and galvanised steel using the same processes may influence impact scores in the categories human health (cancer effects) and freshwater ecotoxicity due to associated differences in emissions of chromium (VI) and zinc (II). The impact scores were the most sensitive to the insulation capacity (*U*-value) of the window, and the ranking of the window alternatives does not change when the EU27 heat mix is used instead of the Danish mix.

Overall, results show that there is a trade-off between types of material used and improved insulation properties of windows. The use of glass fibre-based composite in the W/C has some contribution (up to 12%) to total impacts, depending on the impact category, but the use of the composite substantially improves insulation properties causing an overall reduction in environmental impacts, and leading to the superiority of this window type. The design of windows to ensure better environmental performance should focus on optimising insulation properties of windows, which can be done either by improving the design of the frame or by introducing an additional pane that helps improving insulation properties of the whole window.

39.2 Technical Summary

Nor-win, a Danish-based windows manufacturer, wishes to position itself as a proactive company on the market in terms of environmental sustainability, with the ambition to attract customers demanding more environmentally friendly products. For this purpose, an LCA study was commissioned with the goals (i) to perform a benchmarking of a prototype of a wood/composite (W/C) window made out of glass fibre against three window types currently offered in the market (made of wood (W), wood/aluminium (W/ALU), and PVC) and (ii) to identify environmental hotspots for each window system. The deliverables include (i) detailed life cycle inventory model of the compared systems, including unit process data; (ii) life cycle impact assessment results (in both characterised and normalised forms). We follow EU-recommended practice for characterisation modelling at midpoint to quantify life cycle impacts of four window alternatives, referred to as ILCD. Normalisation was carried out using a set of normalisation references for the year 2010.

The functional unit is “Allow daylight into a residential building through a physical barrier, equivalent to light being transmitted through an area of 1.82 m^2 with visible light transmittance of at least 0.6, for 20 years”. Decision context is micro-level, product or process-related decision support studies, i.e. situation A of the ILCD guideline (EC-JRC 2010). Consequently, the attributional principle was chosen as LCI modelling principle.

Major properties of the four window alternatives are presented in Table 39.1. The window’s ability to prevent heat from escaping the building is described by its heat transfer coefficient—the *U*-value (W m^{-2} K^{-1}). The fraction of light that enters through the window into the building is characterised by its visible light transmittance (T_{vis}).

Table 39.1 Major properties of the four window alternatives

Properties	Window type			
	W	W/ALU	PVC	W/C
Frame material	Mainly wood	Mainly wood and aluminium	Mainly polyvinyl chloride and galvanised steel	Mainly wood and polyamide/glass fibre composite
Glass material	2-layered, coated, sealed with silicone, filled with argon	2-layered, coated, sealed with silicone, filled with argon	2-layered, coated, sealed with silicone, filled with argon	2-layered, coated, sealed with silicone, filled with argon
U-value (W m^{-2} K^{-1})	1.29	1.31	1.36	1.08
T_{vis} (fraction)	0.8	0.8	0.8	0.8
Glass dimensions (m)	1.23 × 1.48	1.23 × 1.48	1.23 × 1.48	1.23 × 1.48

Wood (*W*), wood/aluminium (*W/ALU*), polyvinyl chloride (*PVC*) and wood/composite (*W/C*)

The analysis comprises all life cycle stages from cradle to grave, including transportation and provision of utilities (electricity or heat). The manufacturing technology for all four windows, including the elements composing the pane and the frame, represent the technology, which is currently used by Nor-win and its suppliers. Nor-win is the supplier of primary data used to model the LCI. Ecoinvent and Plastics Europe databases were used for background processes and as source of data for some foreground processes for which no primary data could be retrieved from the suppliers (PlasticsEurope Database 2016; Ecoinvent 2010).

The major assumptions made in inventory modelling include (i) the wood-based windows are sold mainly in Scandinavian countries and Germany, but the use and disposal stages for all windows are modelled using data from processes representative for Denmark; (ii) windows are used only in buildings that are heated by district heating (in Denmark district heating delivers ca. 55% of the total heat demand for buildings); (iii) processes used to model the district heat mix technologies were representative for Norway (except for incineration of bio-waste, which was representative for Switzerland); (iv) energy used for operation of the manufacturing and disassembly facilities for the W/C window is assumed equal to those for other windows, while energy requirements for window disassembly are assumed equal to 1 MJ per kg of dismounted window; (v) losses of materials during production are not considered and all recycled materials replace virgin materials in

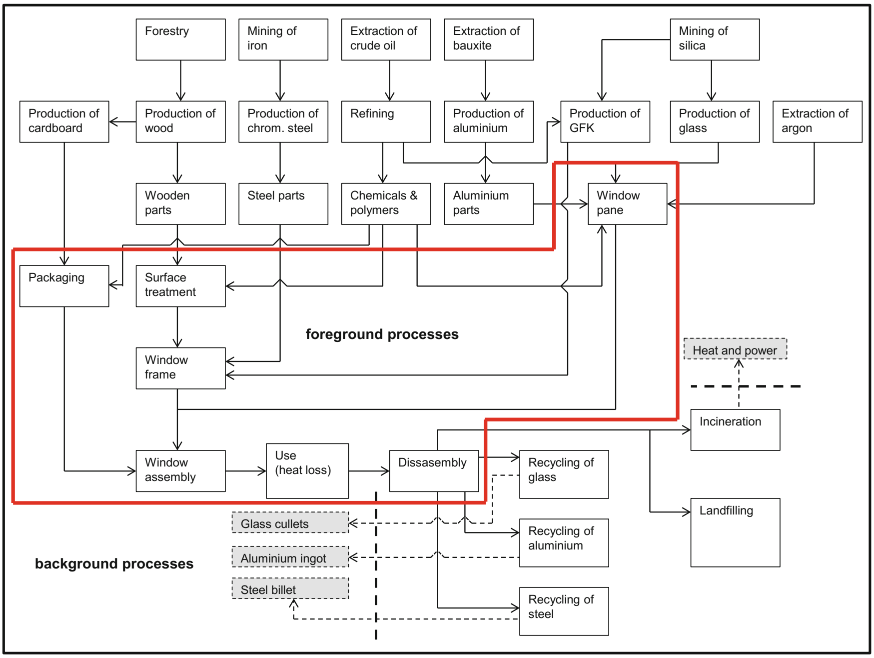


Fig. 39.1 Flow diagram for the wood/composite window (W/C) product system. *Red line* indicates foreground processes. *Grey boxes* indicate avoided processes

the market at a 1:1 ratio without considering any loss of material functionality in the recycling; and (vi) production of chromium steel and galvanised steel was modelled using the same process, while landfilling of EDPM rubber was modelled as that of polypropylene. The flow diagram of the prototype W/C window is presented in Fig. 39.1.

All four window alternatives have impacts within the same order of magnitude, and for most impact categories the impact scores follow the order W/C < W = W/ALU < PVC (Table 39.2). The W/C window has the lowest environmental impact in all 14 impact categories, while the PVC window system has the highest impact scores for 10 impact categories. For nine out of these 10 impact categories the differences in impact scores between the W/C and PVC windows are deemed statistically significant (i.e. the calculated 95% probability ranges of the impact scores do not overlap). For nearly all the non-toxicity-related impact categories, the life cycle impacts of the four windows correspond to approximately 0.1 person equivalents.

Process contribution analysis showed that the main driver of environmental impacts was the production of house heating to compensate for heat losses through the window. The contribution of this process to the total impact is around 90% for climate change, freshwater eutrophication, or resource depletion across all four windows, and above 50% for nearly all other impact categories. The manufacturing stage was relevant for impacts on stratospheric ozone depletion, and ionising radiation (human health) across all windows, and for the impacts on freshwater ecotoxicity, human toxicity (PVC window), and land use (W window). Most of the assumptions made when modelling the LCI were not found to be important for the conclusions, except that modelling of chromium steel and galvanised steel using the same processes may influence impact scores in human health (cancer effects) and freshwater ecotoxicity due to associated differences in emissions of chromium (VI) and zinc (II). The impact scores were the most sensitive to the *U*-value of the window, and the ranking of window alternatives does not change when the EU27 heat mix is used instead of the Danish mix.

Overall, the major conclusions of this LCA are:

I. The W/C window performs significantly better compared to its alternatives in all 14 impact categories. The W/C window is thus the preferable option from an environmental perspective.
II. The PVC window is the least preferred option, as it performs the worst in 11 out of 14 impact categories. This conclusion, however, might change if land use, freshwater ecotoxicity and human health (non-cancer) (where the W window performs significantly worse) are given a higher weight than the rest of the impact categories.
III. The overall environmental performance of the windows is mainly determined by the demand for heat to compensate for heat losses through the window during its use stage. This is true for nearly all impact categories. The *U*-value determines demand for heat, and can thus be considered a key environmental performance indicator of windows.

Table 39.2 Characterised impacts and accompanying 95% probability ranges from Monte Carlo simulations, expressed in category-specific units for each window alternative

Impact category	Unit	Impact score (95% probability range)			
		W	W/ALU	PVC	W/C
Climate change	kg CO_2 eq.	1162 (1134–1189)	1158 (1129–1188)	1232 (1203–1260)	978 (933–1023)
Stratospheric ozone depletion	kg CFC-11 eq.	1.9e−5 (1.8e−5–1.9e−5)	1.6e−5 (1.5e−5–1.6e−5)	1.6e−5 (1.5e−5–1.6e−5)	1.4e−5 (1.4e−5–1.4e−5)
Photochemical ozone formation	kg NMVOC eq.	1.59 (1.55–1.63)	1.57 (1.53–1.61)	1.72 (1.67–1.76)	1.33 (1.26–1.4)
Terrestrial acidification	AE	2.00 (1.95–2.04)	2.00 (1.95–2.05)	2.31 (2.26–2.36)	1.67 (1.6–1.75)
Terrestrial eutrophication	AE	7.14 (6.94–7.35)	7.04 (6.83–7.24)	7.79 (7.56–8.02)	5.96 (5.61–6.32)
Freshwater eutrophication	kg P eq.	0.042 (0.041–0.043)	0.043 (0.041–0.044)	0.046 (0.044–0.047)	0.035 (0.033–0.037)
Marine eutrophication	kg N eq.	0.65 (0.63–0.67)	0.62 (0.60–0.64)	0.68 (0.66–0.7)	0.54 (0.51–0.57)
Freshwater ecotoxicity	CTU_e	2675 (2605–2745)	1755 (1706–1805)	1852 (1809–1895)	1545 (1461–1630)
Human toxicity (cancer)	CTU_h	2e−5 (1.9e−5–2e−5)	1.8e−5 (1.8e−5–1.9e−5)	3.4e−5 (3.3e−5–3.5e−5)	1.6e−5 (1.5e−5–1.7e−5)
Human toxicity (non-cancer)	CTU_h	1.5e−4 (1.5e−4–1.6e−4)	1.3e−4 (1.2e−4–1.3e−4)	1.3e−4 (1.3e−4–1.3e−4)	1.0e−4 (9.9e−5–1.1e−4)
Particulate matter formation	kg $PM_{2.5}$ eq. to air	0.085 (0.083–0.087)	0.082 (0.080–0.084)	0.116 (0.114–0.119)	0.070 (0.067–0.073)
Ionising radiation (human health)	kBq U235 eq.	7.69 (7.56–7.81)	7.99 (7.86–8.12)	8.63 (8.49–8.77)	6.26 (6.07–6.45)
Land use	kg C year	657 (646–668)	405 (399–410)	386 (384–387)	364 (351–377)
Resource depletion (minerals, fossils)	kg Sb eq.	0.0072 (0.0070–0.0073)	0.0074 (0.0072–0.0076)	0.0081 (0.0080–0.0083)	0.0063 (0.0060–0.0066)

W Wood, *W/ALU* wood/aluminium, *PVC* polyvinyl chloride, *W/C* wood/composite
The probability ranges represent the modelled inventory uncertainty, as the uncertainties in the characterisation factors were not known

IV. In addition to processes for generation of heat, other environmental hotspots in the product systems are: production of timber and paint for the W window; the injection moulding process of PVC and production of steel in the PVC window.

V. The use of glass fibre-based composite has some contribution (up to 12%) to total impacts, depending on the impact category, but cannot be considered a hot spot given that the composite substantially improves insulation properties causing an overall reduction in environmental impacts.

VI. Similarly, the use of 3-layered glass instead of 2-layered improves insulation properties resulting in an overall reduction in environmental impacts with the respective heating mix.

VII. The trade-off between impacts from the material used and the improved insulation properties that the material may give the window has to be considered when assessing environmental performance of windows.

Recommendations are given to the commissioner to support eco-design of the new window and greening of the whole value chain:

A. The design of windows to ensure better environmental performance should focus on optimising insulation properties of windows. This can be done by introducing a 3-layered pane, or improving the design of the frame. If the latter is considered, the choice of frame material is important and in each case where new frame material is used in the design of a frame we recommend evaluating (using tools like LCA) whether environmental benefits achieved by improved insulation properties are really sufficient to outweigh potential environmental burden from the use of novel materials. Indeed, if the heat mix changes substantially within the lifetime of the window this could potentially move the hot spots from the use stage to manufacturing and end-of-life stages in which case our recommendations for design of the windows might not hold.

B. Selection of new materials for frame design should consider functional properties of materials in a window design context, i.e. the focus should not be on selection of materials that perform environmentally best per unit mass of the materials, but on selection of materials that perform best considering insulation properties and the amount applied when used in the frame.

C. For the existing W-based windows, improvement potentials lie in selection of paints with lower environmental impact. For the paint applied for maintenance in the use stage, this may be outside the influence of the producer, because it is the window users who will select the type of paint. Our recommendation is to provide information to the users about recommended types of paint.

D. Finally, we recommend to phase-out the PVC window as the option with likely the highest environmental burden overall. If this is not possible, we recommend its redesign through the introduction of a 3-layered pane to improve its insulation properties. Further improvement potentials for the PVC window system lie mainly in selection of cleaner technology for production of PVC frame elements.

The major limitations of the LCA are:

1. Our findings about major drivers of environmental impacts apply to windows where crystal glass is used in the panes with a relatively large (>0.6) visible light transmittance coefficient. They are not thought to be applicable for windows, which change their transparency in response to light intensity (e.g. photochromic windows) where the need for electricity to provide lighting indoor may become an important factor contributing to impacts in the use stage.
2. The disregard of changes in heat mix and heat demand in the future and potential development of more efficient heat supply technologies is another potential limitation. It is uncertain to what extent these will become effective within the time frame of the study (25–30 years). If such is the case, impacts from the manufacturing stage or disposal will become more important in the future (if there is no development of cleaner manufacturing and waste management technologies, which also is uncertain). They may change both the ranking of window alternatives and recommendations given to the commissioner. We expect, however, that in a 20-year time horizon, the use stage will likely remain the most important contributor to total impacts from the window product system, and efforts to design windows with low *U*-values should continue.

39.3 Main Report

Nor-win, a Danish-based windows manufacturer, produces windows for use in residential buildings in Scandinavia (mainly Denmark and Sweden), and some Western European countries (mainly Germany). Existing Nor-win windows on the market are dominated by windows made of wood, a combination of wood and aluminium, or polyvinyl chloride (PVC). Nor-win is currently designing a new type of window made of wood and a composite (glass fibre-reinforced polyamide) to be introduced to the market in 1–2 years, starting with the home market in Denmark. The new window is expected to gain a share of 20–30% of the total current market share of Nor-win. It differs from the existing windows with respect to heat insulation properties, which are improved by combining wood with glass fibre-reinforced plastic in the construction of window frame. The new window is thus expected to have a lower overall environmental impact compared to earlier products from the company. However, a quantitative, life cycle based assessment has not been done yet.

39.3.1 Goal Definition

39.3.1.1 Intended Applications

The study aims to perform a benchmarking for internal use of a wood/composite (W/C) window against three window types made of wood (W), wood/aluminium

(W/ALU), and PVC (PVC) used in Danish residences. With this regard, this study is a comparative case study. However, given that Nor-win will use the results as guidance for the ongoing design of the new window, environmental hotspots for each window system will also be identified. One of the aims of this study is to quantify the trade-off that may occur when potentially reduced environmental impacts from better insulation properties are achieved at the expense of increased impacts from higher demand for materials needed for manufacturing. Overall, the results of this LCA are intended to be used to initiate a greening of the value chains of the four window alternatives.

39.3.1.2 Method Assumptions and Impact Limitations

We follow best, EU-recommended practice for characterisation modelling to quantify life cycle impacts of four window alternatives, referred to as ILCD (EC-JRC 2010; Hauschild et al. 2013). However, even best practice has limitations. The recommended methods currently do not allow for consistent spatially explicit impact assessment. Given that Nor-win operates in Northern Europe, those impacts which occur within this region may be subject to bias, if global-generic characterisation factors are used (Scandinavian soils are for instance quite sensitive to acidification compared to an average European soil). Further, in ILCD, no method has been recommended for dealing with terrestrial and marine ecotoxicity. Thus, impacts on terrestrial and marine ecosystems stemming from emissions of some important stressors, like metals, are not considered in this assessment. In addition, due to insufficient quality of the inventory data, we had to exclude the impact category water use from the set of ILCD methods.

Normalisation was done to relate impact scores to background activities of the society in Europe. However, normalisation references are thought to be underestimated for the toxicity-related impact categories due to the insufficient knowledge of total emissions of the thousands of different chemicals with toxicity potentials in Europe, resulting in overestimation of normalised impact scores for the freshwater ecotoxicity and human toxicity (both cancer and non-cancer effects) impact categories (Laurent et al. 2011).

39.3.1.3 Reasons for Carrying Out the LCA Study and Decision Context

Nor-win wishes to position itself as a proactive company on the market in terms of environmental sustainability, with the ambition to attract customers demanding more environmentally friendly products. For that reason, Nor-win is considering to apply for a Nordic Ecolabel for selected windows in its portfolio, to be used for marketing purposes. Furthermore, the company expects that the LCA study will provide valuable information to be incorporated at the early stages in the development of the new composite window.

The decision context is situation A as the decisions taken by Nor-win stakeholders will primarily have an internal influence (i.e. in supporting the eco-design of the new type of window) and will not result in structural consequences on the market because the share of Nor-win of total window market in Europe is small (ca. 3%). This is mainly because Nor-win is a relatively minor customer for its suppliers and the market production capacity will not be influenced if changes in the choice of suppliers are introduced based on the LCA results.

39.3.1.4 Target Audience

The target audience is environmental and design departments at Nor-win. The company has limited knowledge about life cycle concepts and has neither conducted nor commissioned an LCA before. However, the company has recently employed a designer who is familiar with eco-design principles.

39.3.1.5 Comparisons Intended to Be Disclosed to the Public

This comparative LCA study is not intended to be a comparative assertion disclosed to the public.

39.3.1.6 Commissioner of the LCA Study and Other Influential Actors

This study is commissioned and fully financed by Nor-win. The team carrying out the LCA includes an employee from Ecolabelling Denmark at Danish Standard (Dansk Standard, DS), an organisation that is monitoring and developing ecolabel standards for various products, including windows. Ecolabelling Denmark is thus an influential actor.

39.3.2 Scope Definition

39.3.2.1 Deliverables

This is both a comparative LCA study (for internal use) and an environmental hotspot analysis carried out for each window alternative (see Sect. 2.1). The deliverables include (i) detailed life cycle inventory model of the compared systems, including unit process data; and (ii) life cycle impact assessment results (in both characterised and normalised forms).

39.3.2.2 Function, Functional Unit, and Reference Flows

Function. The four window types are made of different materials and are compared on the basis of their main function, which is allowing light inside the building. The fraction of light that enters through the window into the building is characterised by a parameter called visible light transmittance (T_{vis}). T_{vis} can vary between windows depending on the type and properties of the windowpane, but for windows with panes made of crystal glass it is generally not lower than 0.6. The visible light transmittance is a relevant parameter to consider because light transmittance properties of some windows (like the photochromic or electrochromic ones) may vary, depending on other factors (e.g. light intensity), in which case increased need for indoor lighting should be considered when modelling life cycle inventories. This was not considered relevant in our case study where all four windows have pane made out of crystal glass of constant (and relatively high, $T_{vis} > 0.6$) light transmittance properties. The secondary function of the window (i.e. its ability to transfer heat) was considered by crediting the system for the heat loss in the use stage (as will be explained in detail in Sect. 39.2.3). While all windows must allow daylight into a building (obligatory property), they may differ in some of the positioning properties (Table 39.3).

The window's ability to conduct heat is described by its heat transfer coefficient, the *U*-value (W m^{-2} K^{-1}). The *U*-value is a measure of how well a *window* prevents heat from escaping the building. The lower the *U*-value the lower is the heat loss. The *U*-value depends on the type of material and design of the window frame, and properties (thickness, coating, and number of layers) of the windowpane and on the properties of the material between the panes. The *U*-value is usually measured and provided by the manufacturers. The *U*-value is thus an important parameter because any heat loss through the window must be compensated by providing extra heating to the indoor environment that the window shields. It is estimated that losses through windows can account for 25% of the total heat loss in a residential building (Natural Resources Canada 2015). Note that both window frame and windowpane can be characterised by a *U*-value. The *U*-value used here refers the window as a whole. Major properties of the four window alternatives are presented in Table 39.4.

Table 39.3 Obligatory and positioning properties of windows in this case study

Obligatory property	Positioning properties
• Allow daylight into a building through a physical barrier	• Thermal and noise insulation • Allow ventilation between indoor and outdoor • Provide aesthetic functionality to the building • Protection against breaking into the building

Table 39.4 Major properties of the four window alternatives

Properties	Window type			
	W	W/ALU	PVC	W/C
Frame material	Mainly wood	Mainly wood and aluminium	Mainly polyvinyl chloride and galvanised steel	Mainly wood and polyamide/glass fibre composite
Glass material	2-layered, coated, sealed with silicone, filled with argon	2-layered, coated, sealed with silicone, filled with argon	2-layered, coated, sealed with silicone, filled with argon	2-layered, coated, sealed with silicone, filled with argon
U-value (W m^{-2} K^{-1})	1.29	1.31	1.36	1.08
T_{vis} (fraction)	0.8	0.8	0.8	0.8
Glass dimensions (m)	1.23 × 1.48	1.23 × 1.48	1.23 × 1.48	1.23 × 1.48

Wood (*W*), wood/aluminium (*W/ALU*), PVC or wood/composite (*W/C*)

Table 39.5 Life times and reference flows needed to fulfil the functional unit for the four window alternatives

Property/reference flow	Window type			
	W	W/ALU	PVC	W/C
Life time of the window frame (years)	40	40	30	40
Life time of the window pane (years)	20	20	20	20
Reference flows (numbers)				
Window frame	0.5	0.5	0.67	0.5
Window pane	1	1	1	1
Packaging	1	1	1	1
Paint for window frame	8	0	0	0

Functional unit. All four windows are compared on the basis for the following functional unit: “Allow daylight into a residential building through a physical barrier, equivalent to light being transmitted through an area of 1.82 m^2 with visible light transmittance of at least 0.6, for 20 years”. This definition allows for a fair comparison between windows with different *U*-values. Note, however, that it does not allow for a comparison with an empty hole in the house (which although allows daylight into a building, is not a physical barrier).

Reference flows. Considering the different life times for window frames and panes, the reference flows in Table 39.5 are derived as needed to provide the service defined in the functional unit. It is assumed that the pane will be changed once in windows’ lifetime (specifically, after 20 years) and that the window is used for the time equal to the lifetime of the frame. Please note that reference flows for pane and frame would be equal if the whole window is to be replaced after 20 years equal to the expected life time of the pane (and irrespective of the life time of the frame). Whether this is the case will depend on factors like trends in design, the overall state of the building, or the frequency of change in the ownership of the apartment where the window is installed. These factors were not considered here.

39.3.2.3 LCI Modelling Framework

Nor-win's introduction of a new window and improvements in heat insulation properties of existing windows are not expected to have large structural changes on the market (like installation of new composite factories or decommissioning of existing heat pumps). Thus, the decision context is micro-level, product or process-related decision support studies, i.e. situation A in the ILCD Guideline (EC-JRC 2010), suggesting that the attributional principle be chosen as LCI modelling framework. This implies that the systems are modelled depicting existing value chains, i.e. using current Danish electricity and heating mix, and Danish recycling rates for end-of-life scenarios. Consistently with the micro-level decision context, system expansion was done to credit for the heat loss in the use stage using average Danish data. Note, that we applied system expansion (through crediting) using average processes in this attributional approach, consistently with both ILCD and the ISO hierarchy to solving multifunctionality, although system expansion using marginal processes has traditionally been considered for the consequential approach to inventory modelling (allocation has traditionally been used for the attributional approach).

Apart from the secondary function of the window (i.e. its ability to transfer heat), other processes downstream can also have secondary functions or co-products, namely recycling operations (producing recycled steel, aluminium, glass, or recycled PVC). As system expansion is the preferred approach to solving multifunctionality, materials produced from recycled content are credited using virgin materials, i.e. aluminium ingots, steel billet, glass cullets (for all windows), and additionally PVC granulate mix (for PVC window), where all virgin materials and PVC granulate are produced using average technologies. Similarly, incineration of some materials in the end-of-life stage produces heat and power, which is credited using average Danish heat and power mixes. Secondary functions in upstream processes also exist (e.g. naphtha cracking, waste incineration), but these secondary functions had to be handled according to how the database (i.e. ecoinvent v.2.1) did it, so using allocation.

39.3.2.4 System Boundaries and Completeness Requirements

System boundaries. The analysis includes all life cycle stages from cradle to grave (Fig. 39.2). Processes include for all product systems raw material extraction, primary and secondary material production and upstream processes such as mining of metal ores and extraction of crude oil within the system boundaries. Raw materials are transported to metal smelters or refineries to produce virgin metals, fuels and plastics. Similarly, forestry is included to produce wood. These materials are used to produce specific parts from which window components (window frame and windowpane) are made. Assembled windows are packaged and transported to retailers, and from there to residential buildings, in which they are mounted and provide their function. The use stage includes maintenance painting of the wood window (W), and cleaning of all windows. At the end of life, windows are dismantled and transported to a waste handling facility for disassembly. Steel, aluminium and glass are mainly recycled. Landfilling and incineration with heat recovery apply to cardboard, wood, and plastics, and to the remaining, non-recycled fractions of steel, aluminium and glass.

Completeness requirements. As the LCA includes a hotspot analysis, no processes should ideally be excluded from the system boundaries based on their similarity between the four window systems. Yet, we excluded:

(i) Cleaning of windowpane. Although potentially interesting for the hot spot analysis, Nor-win has little control of the cleaning process (e.g. frequency of the cleaning, detergent type). Thus, the inclusion of cleaning is not that important for the goal of the study (that is, to support guidance for the ongoing design of the new window and green supply chain for the existing windows).

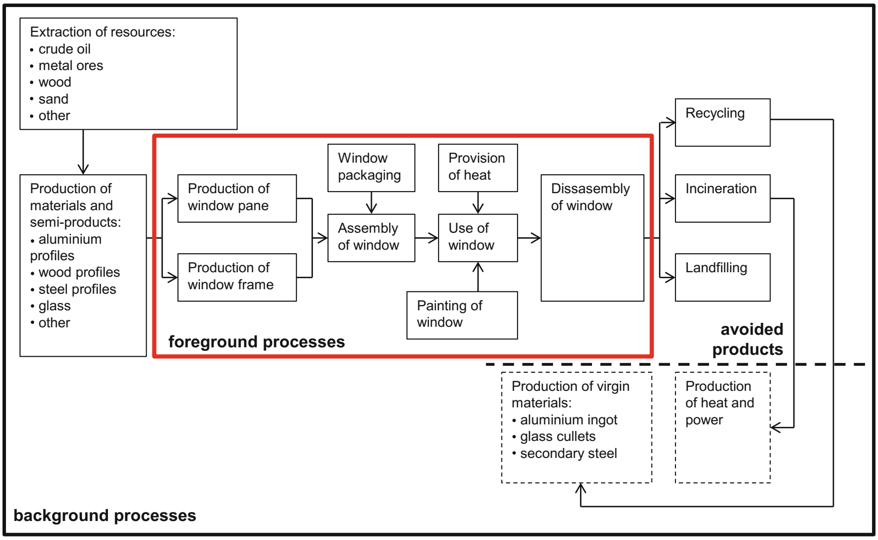


Fig. 39.2 System boundaries for the product systems of the four window alternatives. Transportation and provision of utilities other than heat (e.g. electricity) are included inside the system boundaries but not shown in the figure in order to make it more legible

(ii) Capital equipment such as buildings or machines, unless already integrated in aggregated unit processes of the background system, is excluded. This is common practice in process-based LCA.

(iii) Materials contributing to less than 5% of the total mass of the window are cut-off, excepting substances for surface treatment of the window frame, which are expected to be toxic and hence potentially contribute significantly to some impact scores even with much smaller quantities applied.

39.3.2.5 Representativeness of LCI Data

Technological representativeness. The manufacturing technology for all four windows, including the elements composing the pane and the frame, should (ideally) represent the technology that is currently used by Nor-win and its primary suppliers. This technology is characterised by relatively high efficiency (in terms of material output per day), mainly due to the use of modern (<5 years old) machines and production lines and the employment of relatively new (<7 years old) technological solutions (like those used for impregnating and painting wooden frame, or painting aluminium). Thus, the data for window manufacturing should primarily come from Nor-win and its suppliers. Alternatively, other Scandinavian or European window manufacturers (and European suppliers) that use relatively modern technology can be used as source of data for manufacturing to compensate for missing data.

Data for background processes, like extraction of metal ores and production of raw metals, or extraction of fossils, should ideally represent the average technology currently used globally. It is sufficient that this data comes from generic databases.

Geographical representativeness. Geographical coverage is similar for all four windows (Table 39.6). Wood for the frame originates from forest in Finland, while the pane together with the glass is produced in Sweden. Polyvinyl chloride for the PVC window is produced in Germany. Thus, in the absence of Nor-win and supplier-specific data, they should originate from associations and companies located in Europe. End-of-life data should be the average for the main market, which is either Denmark (W, W/ALU and W/C) or Germany (PVC).

Temporal representativeness. The data for manufacturing processes should be representative for windows produced from 2015 to 2020, i.e. a 5-year time horizon for window manufacturing (the product development takes about 1 year and is not considered important). The average window lifetime is assumed to be 30 (PVC) or 40 years (W, W/ALU and W/C). However, to comply with the definition of the functional unit, the use stage and end-of-life processes should (ideally) be representative for the 25–30 year time horizon, over which the products will be in use or disposed of. Figure 39.3 shows temporal frames of the windows.

Table 39.6 Geographical scope for life cycle stages and central unit processes in the window frames case study

Stage	Window type			
	Wood	Wood/aluminium	PVC	Wood/composite
Materials	Metal ores: not known			
	Crude oil: Norway, Russia, Middle East			
	Forestry: Finland		–	–
Manufacturing	Glass pane: Sweden			
	Wood frame: Scandinavia	Wood/aluminium frame: Scandinavia	PVC frame: Scandinavia	Composite frame: Scandinavia
	Other elements: mainly Europe	Other elements: mainly Europe	Other elements: mainly Europe	Other elements: mainly Europe
	Assembly: Denmark			
Use (heat supply)	Mainly Scandinavia, Germany	Mainly Scandinavia, Germany	Mainly Germany	Mainly Scandinavia
Disposal	The same as the use stage			

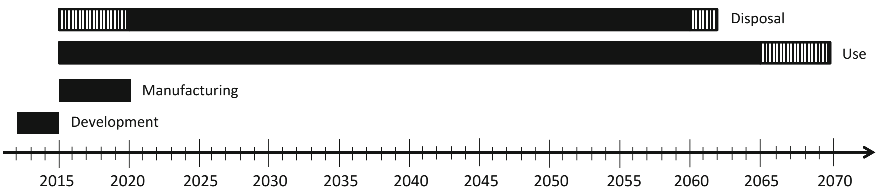


Fig. 39.3 Temporal scope of the W, W/ALU and W/C windows expressed for different life cycle stages. Manufacturing starts in 2015 and continues for 5 years, thus the overall time horizon for the use stage is 5 years longer than the 20-year duration of the use stage for individual window (indicated with a *black-white pattern*). Similarly, the temporal horizon for the disposal stage may start right after the first window had been produced, and end 2 years after end of the use stage (as indicated with the *black-white pattern*). The temporal scope for the use and disposal of the PVC window is 10 years shorter compared to the three other windows (not shown). Note that the temporal scope looks at the time horizon of the window life cycle (i.e. 40 years), regardless of the duration considered in the functional unit (in our study equal to 20 years)

39.3.2.6 Basis for Impact Assessment

ILCD's recommended practice for characterisation modelling is employed as life cycle impact assessment method (EC-JRC 2012; Hauschild et al. 2013). The ILCD is a combination of state of the art methods for LCIA (as of 2009). Analysis of the sensitivity of the results to alternative LCIA methods was not deemed necessary since the results are for internal use only. Modelling impacts at midpoint is considered sufficient given the goal of the study (comparative assessment and identification of hotspots). Normalisation was performed using the set of normalisation references presented for year 2010. The following impact categories are included in the ILCD: climate change (unit: kg CO_2 eq.), ozone depletion (kg CFC-11 eq.) photochemical ozone formation (kg NMVOC eq.), terrestrial acidification (AE, accumulated exceedance), terrestrial eutrophication (AE, accumulated exceedance), freshwater eutrophication (kg P eq.), marine eutrophication (kg N eq.), freshwater ecotoxicity (CTU_e, comparative toxic unit for ecosystems), ionising radiation (human health, in kBq U235 eq.), particulate matter/(kg $PM_{2.5}$ eq. to air), human toxicity (cancer effects, in CTU_h for human health), human toxicity (non-cancer effects, in CTU_h for human health), land use (kg C year), and resource depletion (mineral and fossils, in kg Sb eq.).

Product systems were modelled in GaBi, version 4.3 (PE International, Germany; renamed to thinkstep). Because the ILCD LCIA method was not implemented in GaBi at the time of the study, characterisation factors for the ILCD methods (version 1.0.3, 01 March 2012) were downloaded from the Life Cycle website of the European Commission (http://lct.jrc.ec.europa.eu/assessment) and were imported into the software. For those impact categories where ReCiPe 2008 (Goedkoop et al. 2009) is the recommended method (6 categories in total), impact scores were calculated using the original set of ReCiPe (version 1.05) characterisation factors as implemented in GaBi. Normalisation references are for the EU27 in the reference year 2010 as presented in Benini et al. (2014). The LCIA methods and normalisation factors are presented in Annex, Sect. 39.4.1.

39.3.2.7 Requirements for Comparative Studies

Although requirements for a comparative study (like quality requirements, exclusion of identical processes and interpretation in light of affected stakeholders) are only applicable to studies reported at level 3 (that is, comparative studies to be disclosed to the public), we note that in our case study comparison has been made using the same functional unit, system boundaries omit common processes only (i.e. window washing), and data quality is the same between the compared windows (e.g. primary data come from manufacturer). Thus, the comparison between the four window systems is fair and requirements for comparative studies are met. The readers should note, however, that although we quantified inventory uncertainties, comparison could not be made taking into account correlation between inventory uncertainties of those inventory processes which are the same for the compared window systems (as will be explained in detail in Sect. 39.3.5). Thus, in some cases there may be statistically significant difference in impact scores between window systems, even if that is not apparent in our analysis. On the other hand, uncertainties in background processes were not considered, which may, at least partially, outweigh a potential decrease in uncertainty due to correlations.

39.3.2.8 Critical Review Needs

This is a comparative study but since it is not intended for disclosure to the public, there is no obligation for a critical review by a third-party panel.

39.3.3 *Life Cycle Inventory Analysis*

39.3.3.1 LCI Model at System Level

Flow diagrams show the product systems of the four windows in Figs. 39.4, 39.5, 39.6 and 39.7. Comparison between the flow diagrams shows that many processes are the same for the four windows (e.g. mining of silica and production of glass, or mining of iron and production of chromium steel). Yet, magnitude of flows often varies between the systems (not shown).

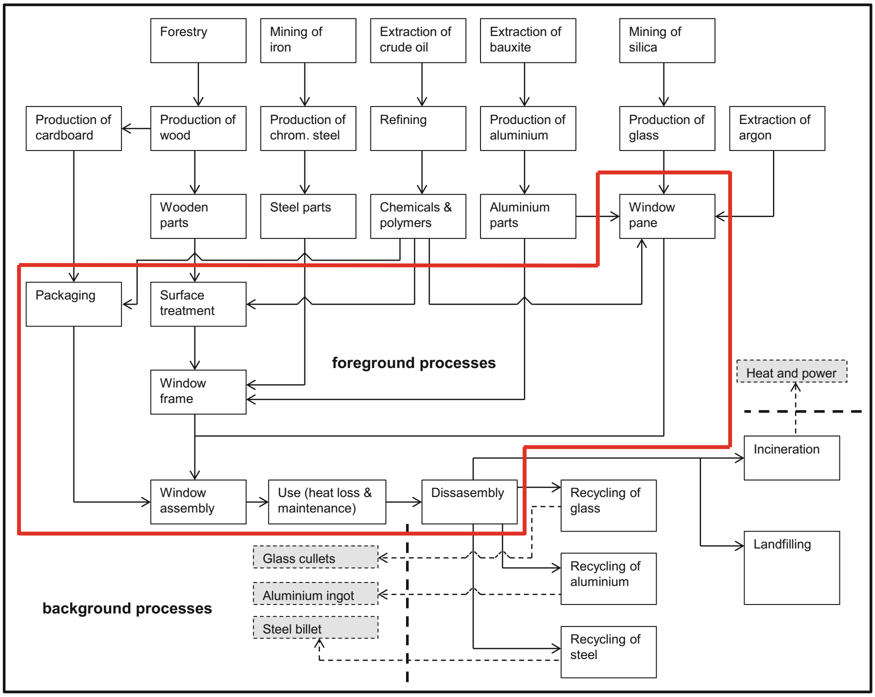


Fig. 39.4 Product system of the wood window (W). *Red line* indicates foreground processes. *Grey boxes* indicate avoided processes

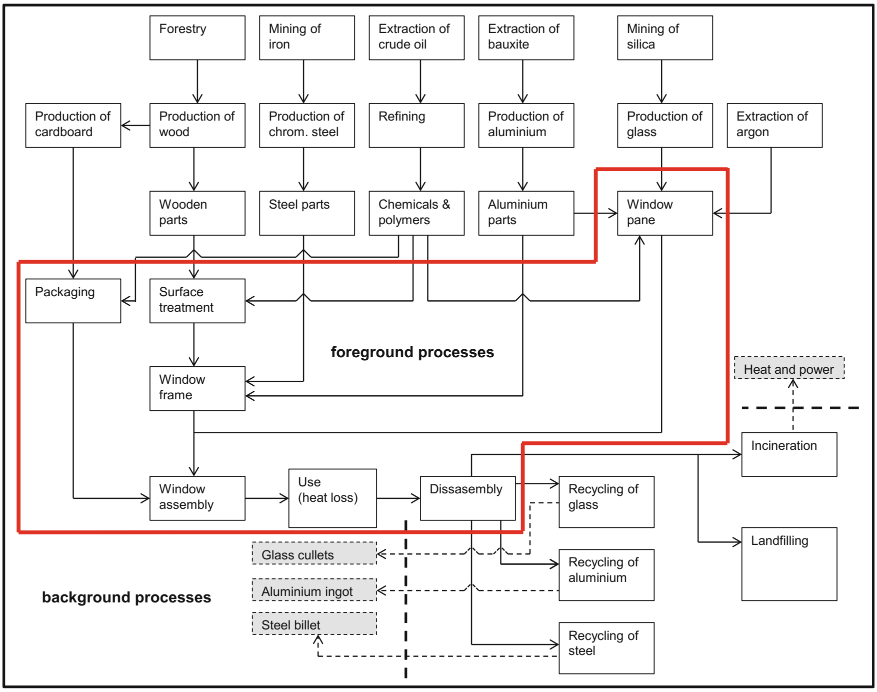


Fig. 39.5 Product system of the wood/aluminium window (W/ALU). *Red line* indicates foreground processes. *Grey boxes* indicate avoided processes

39.3.3.2 Data Collection

Data used to model life cycle inventories for the foreground systems were collected from two sources: (i) Nor-win, who provided primary data related mainly to energy use in the manufacturing and bills of materials and (ii) ecoinvent and Plastics Europe databases for foreground processes where primary data could not be achieved (PlasticsEurope Database 2016; Ecoinvent 2010). The primary data from Nor-win meet the quality requirements given in Sect. 39.3.5. The data are synthesised in Table 39.7.

39.3.3.3 System Modelling Per Life Cycle Stage

Below, we present details of the system modelling, the data collected and treatment, and major assumptions. The full list of major and minor assumptions is given in the report Annex, Sect. 39.4.3.

Materials stage. Bills of activities required to produce one window are given in Table 39.7, with details on the bill of materials presented in Annex, Sect. 39.4.2 (Table 39.12). Amounts of materials in each window are provided by Nor-win.

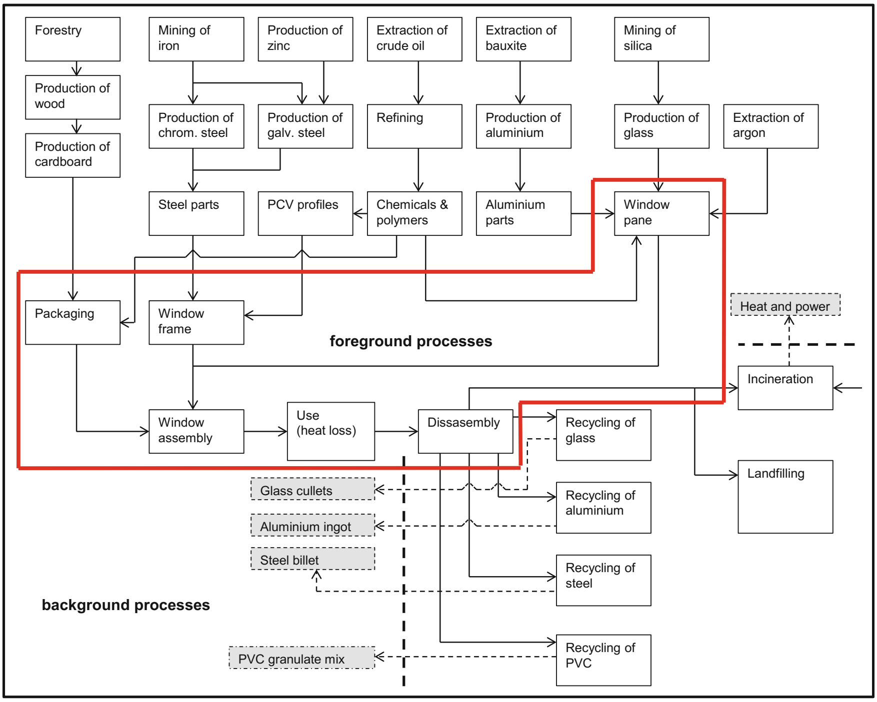


Fig. 39.6 Product system of the polyvinyl chloride window (PVC). *Red line* indicates foreground processes. *Grey boxes* indicate avoided processes

Data for W, W/ALU and PVC windows are precise, because these windows are already on the market and detailed information is available. Data for the W/C window are considered sufficiently accurate to be used in modelling, because the prototype of the window has been produced. Note that based on the outcome of this study, the W/C window may be redesigned, bringing about a change in amounts of some materials in which case the LCA may have to be updated with the new numbers. It is not expected that this change will be higher than 5% for any window frame material. No major assumptions were made for the materials stage.

Manufacturing stage. Data on electricity use for production come from measurements of the actual processes and are provided by Nor-win. These data are of high quality and are considered certain. Data on electricity requirements for assembly of the W/C window frame are less certain, and are initial estimates provided by Nor-win. The three major assumptions made in the production stage are (i) losses of materials during production are not considered, (ii) energy used for operation of the manufacturing and window disassembly facilities for the W/C window is assumed equal to numbers for other windows, and (iii) energy requirements for window disassembly are assumed equal to 1 MJ per 1 kg of dismounted window.

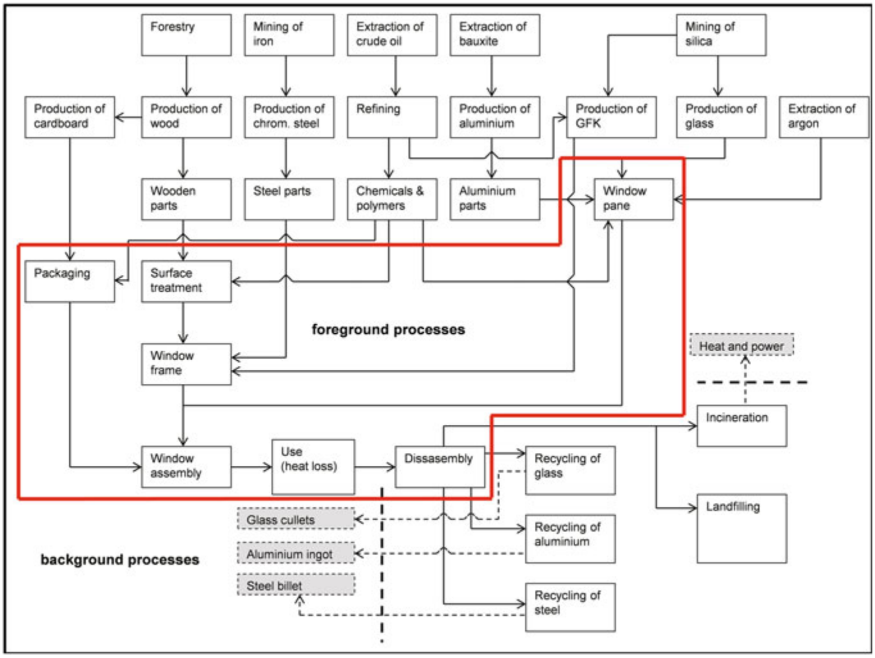


Fig. 39.7 Product system of the wood/composite window (W/C). *Red line* indicates foreground processes. *Grey boxes* indicate avoided processes

Use stage. Data on heat use during the use stage are calculated using the *U*-values and average temperature difference between outdoor and indoor environment (Table 39.7). Several assumptions were made for the use stage. First, we modelled the heat loss based on the annual average temperatures indoor and outdoor, without considering the temperature dynamics during the year. Second, we assumed that there is no shift in the source of heat (e.g. towards wind-driven electricity) over the lifetime of the window. Third, we assumed that the windows are used only in buildings to which heat is provided by district heating. In Denmark, district heating was estimated to deliver 55% of the total heat demand for buildings in 2010 (Dyrelund and Lund 2009). Fourth, processes used to model the district heat mix technologies were representative for Switzerland, or were based on European processes for the generation of heat from the sources included in the study, as no Danish processes were available in ecoinvent 2.2. The fifth assumption is that processes for generation of heat from incineration of straw and non-renewable waste in the Danish heat mix were modelled as incineration of bio-waste, while heat generation from biomass in the EU27 heat mix was modelled as incineration of bio-waste combined with combustion of wood pellets (50:50).

Disposal stage. Waste treatment options are based on the data retrieved from Eurostat (2016). Glass, aluminium and steel are mainly recycled, and wood is

Table 39.7 Metadata including model parameters and data sources for foreground processes for the four window alternatives

Parameter	Value				Unit	Note	Source
	W	W/ALU	PVC	W/C			
Materials							
Frame materials	See Annex, Sect. 39.4.2, Table 39.12				kg	In addition to materials presented in Table 39.12, other materials used to produce the frames include acrylic binder, triethylene glycol and wood preservative which are used in small amounts (<1% of total frame mass). Bills of materials are retrieved from the producer	Measured
Pane materials	See Annex, Sect. 39.4.2, Table 39.12				kg	In addition to materials presented in Table 39.12, synthetic rubber (ethylene propylene diene monomer, EDPM is used in smaller amounts (<2–6% of total pane mass). Bills of materials are retrieved from the producer	Measured
Thickness of glass underlying window pane	5				mm	Nominal thickness as provided by the producer	Measured
Packaging	See Annex, Sect. 39.4.2, Table 39.12				kg	Packaging is made of polyethylene and recycled cardboard. Bills of materials are retrieved from the producer and are presented in Table 39.12	Measured
Manufacturing							
Electricity for production of window frame	15	21	24	30	MJ	The data come from measurements of the actual processes and are provided by the producer, apart from the W/C window for which the producer assumed that electricity required for assembly of the frame for the W/C window is 2 times higher than for the W window	Measured or assumed
Electricity for production of window pane	5	5	5	5	MJ	The data come from measurements of the actual processes and are provided by the producer	Measured
Electricity for mounting window frame and window pane into a window (MJ)	38	40	46	50	MJ	The data come from measurements of the actual processes and are provided by the producer, apart from the W/C window for which the producer assumed that electricity required for mounting of thee W/C window is 1.3 times higher than for the W window	Measured or assumed

(continued)

Table 39.7 (continued)

Parameter	Value				Unit	Note	Source
	W	W/ALU	PVC	W/C			
Electricity for operation of the manufacturing facility	80	80	80	80	MJ	The data is provided by the producer for the plant and is scaled to one window basing on the electricity bills and production capacity while taking into account electricity used for production and mounting	Measured
Heat demand							
Heat loss per year	741	752	781	620	MJ/year	Heat loss is directly proportional to the *U*-value and the window area and to the temperature difference between indoor and outdoor environment, and is calculated using the formula $\Phi_t = U \cdot A \cdot (\theta_i - \theta_e)$ where Φ_t [W] is the heat loss, U [W m^{-2} K^{-1}] is the *U*-value, A [m^2] is the heat exchange area; θ_i is the indoor temperature (K), and θ_e is the outdoor temperature (K)	Calculated
Indoor temperature	17	17	17	17	°C	Annual average indoor temperature in residential buildings	Assumed
Outdoor temperature	7.7	7.7	7.7	7.7	°C	Annual average outdoor temperature in Denmark, calculated based on the temperature data retrieved for year 2014 from DMI (2016)	Calculated
Maintenance of window							
Painting needed for painting of 1 window	0.6	0	0	0	kg	Approximately 1 L of paint is needed for a window frame area of 1 m^2 (based on data from a single paint producer)	Assumed
Transportation distances and means							
Elements composing window frame and window pane	1240	1110	830	310	km	Distance between suppliers of elements underlying window frame and windowpane and location of the producer. Calculated using Google maps. Transport by truck 34–40 t, EURO4	Calculated

(continued)

Table 39.7 (continued)

Parameter	Value				Unit	Note	Source
	W	W/ALU	PVC	W/C			
Window from producer to warehouse	300	300	300	300	km	Distance between producer and warehouse. Calculated using Google maps. Transport by truck 34–40 t, EURO4	Calculated
Window from warehouse to residential building	100	100	100	100	km	Distance between the warehouse and residential building including retail. The location of final user is unknown and distance had to be assumed. Transport by truck 12–14 t, EURO3	Assumed
Window from residential building to disposal/ recycling site	100	100	100	100	km	Distance between the residential building and disposal/ recycling site. The locations are unknown and thus the distance had to be assumed. Transport by truck 12–14 t, EURO3	Assumed
Packaging from residential building to the disposal site	85	85	85	85	km	Distance between the warehouse and residential building including retail. The location of final user is unknown and distance had to be assumed. Transport by truck 12–14 t, EURO3	Assumed
Disassembly and disposal							
Electricity for disassembly of window	90	77	91	76	MJ	It is assumed that electricity consumption is equal to 1 MJ per 1 kg of dismounted window	Assumed
Waste treatment options	See Sect. 39.4.2, Table 39.13				%	Disposal according to the Danish waste policy (Eurostat 2016). Treatment rates are presented in Annex, Sect. 39.4.2, Table 39.12	Measured

Wood (*W*), wood/aluminium (*W/ALU*), PVC or wood/composite (*W/C*)
Note that the values are scaled to one window used for one year, not to the functional unit of the window systems

incinerated. Other materials are mainly incinerated, or landfilled. PVC is technically recyclable but not to the extent as for other plastics (30%). The remaining part of PVC is landfilled. The composite (glass fibre/polyamide) is technically difficult to recycle, and is assumed 100% incinerated. Details of end-of-life options are presented in Annex, Sect. 39.4.2 (Table 39.13). The two major assumptions are (i) all recycled materials replace virgin materials in the market, i.e. glass cullets, aluminium ingot, steel billet, and PVC granulate mix, at a 1:1 ratio, i.e. without considering any loss of material functionality in the recycling; and (ii) although the wood-based windows are sold mainly in Scandinavian countries and Germany, the use and disposal stages for all windows are modelled using data from processes representative for Denmark, e.g. Danish heating and electricity mixes and waste management systems.

Transportation. Transportation distances and means are either provided by Nor-win or assumed. The data provided by Nor-win are considered sufficiently accurate, whereas the assumed data are considered uncertain.

39.3.3.4 Basis for Sensitivity and Uncertainty Analyses

To test the influence of the assumptions made on the results of the LCA, sensitivity analyses were performed, followed by uncertainty and variability analyses.

Sensitivity analyses. First, to identify which of the parameters influence impact scores the most, and to provide a basis for uncertainty and variability analysis, we calculated normalised sensitivity coefficients ($X_{IS,k}$), according to Eq. 39.1 (e.g. Prommer et al. 2006):

$$X_{IS,k} = \frac{\Delta IS/IS}{\Delta a_k/a_k} \tag{39.1}$$

where $X_{IS,k}$ is the normalised sensitivity coefficient of impact score (IS) for perturbance of a parameter k, a_k is the default value of parameter k, Δa_k is the perturbation of parameter a_k, IS is the calculated impact score for parameter value a_k, and ΔIS is the change of the impact score that results from the perturbation of parameter a_k. The following parameters were tested: amount of wood, aluminium, steel composite (W/C window only), and PVC (PVC window only) in the window frame, the amount of glass in the pane, amount of paint for manufacturing, electricity needed for assembly, U-value, and transportation distance from Nor-win to retailers. All input parameters were perturbed by 10%, which is a realistic range around the expected values. $X_{IS,k}$ equal to 1 means that a 10% increase in parameter value brings about a 10% increase in the impact score. Generally, a parameter is considered to have medium sensitivity if $X_{IS,k} > 0.3$, and large sensitivity if $X_{IS,k} > 0.5$. In this study, a parameter is considered important when $X_{IS,k} > 0.3$.

Second, in addition to testing sensitivity to individual parameters through computation of normalised sensitivity coefficients, perturbing each parameter at once, a separate sensitivity check was done, where several parameters expected to be important were perturbed at once. The overview of the two sensitivity scenarios considered is given in Table 39.8. Scenario 1 reflects a situation where the window is used by an average European residence rather than a Danish residence. Scenario 2 reflects the situation where a 3-layered windowpane is used instead of a 2-layered one, which improves insulation properties of the whole window (without any considerable influence on visible light transmission properties). This scenario was included to identify potential for improvements of existing and new windows. Note, that over the coming 20 years we may see a shift in the heat source (e.g. towards wind-driven electricity) but it is uncertain to what extent these will become effective within the time frame of the study (25–30 years). On the other hand, we may also witness the development of cleaner manufacturing and waste management technologies in 20 years (which is also uncertain). Thus, the potential change in heat mix and change in manufacturing and waste management systems were not considered in the sensitivity analysis.

Uncertainty and variability analysis. Parameter uncertainties stem from the imprecision in knowledge about the actual value of a parameter, e.g. electricity use during window assembly. By contrast, variability is the inherent variance that will exist between similar processes depending on technological level and spatial location, e.g. transportation distance from factory to retail Steinmann et al. (2014).

Table 39.8 Sensitivity scenarios and corresponding model parameters

Sensitivity parameters	Baseline scenario	Sensitivity scenario	
		Scenario 1	Scenario 2
Use location[a]	DK	EU27	DK
Disposal route[b,e]			
Heat mix[c,f]			
Electricity mix[d,g]			
Pane design	2-layered	2-layered	3-layered[h]

[a]*DK* Denmark; *EU27* European Union's 27 member states

[b]Please see Annex, Sect. 39.4.2 (Table 39.13) for details of end-of-life options in DK and EU27

[c]Danish heating mix in 2010 was based on: natural gas (24%), coal (23%), straw (8%), wood chips (12%), wood pellets (10%), non-renewable waste (17%), oil (2%), and other sources (4%) (Energynet 2012)

[d]Danish electricity mix in 2010 as based on: hard coal (36%), natural gas (14%), wind power (15%), oil (2%), import from Sweden (14%), Norway (10%), Germany (3%), and other sources (6%) (Ecoinvent 2010)

[e]Compared to Danish disposal routes the EU27 disposal routes in 2010 is characterised by lower frequency of recycling and/or incineration, and increased frequency of landfilling (Eurostat 2016). The disposal options are summarised in Annex, Sect. 39.4.2 (Table 39.13)

[f]EU27 heat mix in 2010 was based on: natural gas (57%), oil (21%), biomass (13%), and coal (9%) (Connolly et al. 2012)

[g]EU27 electricity mix was 2010 is based on: nuclear power (28%), coal and peat (27%), natural gas (27%), hydropower (11%), wind power (4%), oil (3%), biofuels (3%), and non-renewable waste (7%) (Ecoinvent 2010)

[h]3-layered windows have improved insulation properties thanks to smaller *U*-values, which were reduced by 25% for the W, W/ALU, and PVC windows, and by 30% for the W/C window

Table 39.9 Uncertain or variable parameters included in the Monte Carlo simulation and the associated relative standard deviation, expressed in percentage

Uncertain or variable parameter	Mean (relative standard deviation)[a]			
	W	W/ALU	PVC	W/C
Amount of wood in the frame[b]	30 (1%)	9.2 (1%)	0 (0%)	9.2 (2.5%)
Amount of steel in the frame[b]	0.5 (1%)	1.2 (1%)	15.1 (1%)	1.2 (2.5%)
Amount of glass in the pane[c]	56 (0.5%)	56 (0.5%)	56 (0.5%)	56 (0.5%)
U-value of the window[d]	1.29 (1.5%)	1.31 (1.5%)	1.36 (1.5%)	1.08 (3%)

[a]Relative standard deviation (also known as coefficient of variation, CV) is equal to sample standard deviation divided by sample mean, expressed in percentage. Sample standard deviation was estimated using an empirical rule that the sample standard deviation is equal to one fourth of the whole parameter range (equal to the difference between maximum and minimum value)
[b]Change in amounts of wood and steel in the frame depend mainly on losses in the production, and are expected to be maximum 2% for W, W/ALU and PVC windows, and 5% for the W/C window, because of the ongoing development of the latter. These values are realistic values provided by Nor-win based on the information retrieved from suppliers
[C]Change in the amount of glass is expected to be by maximum 1%. Again, this value was provided by Nor-win
[d]Although the *U*-value is considered as an inherent property of a window, the actual amount of heat exchanged depends on other factors, like the quality of the work during window installation, type and quality of insulation used to install the window in the wall, or type and properties of walls. To account for this variability, a maximum change in the *U*-value of 3% was used for W, W/ALU and PVC windows, based on the information from Nor-win. For the W/C window, 6% was used to calculate minimum and maximum *U*-values (again, because it is ongoing product development)

Here, parameter uncertainty was assessed together with variability by means of a Monte Carlo simulation. Only parameters that were found important ($X_{\mathrm{IS},k}$ > 0.3) in the sensitivity analysis, for any of the considered impact categories for either window design option, were considered. In total, four parameters where considered (Table 39.9). They were assigned relative standard deviations derived from the expected range of parameter values. The uncertainty ranges and number of uncertain parameters is higher for the W/C window, because this window is still in under development and very accurate bills of materials and performance parameters (*U*-value) are not known. We assumed normal distributions of all parameters mainly because this is one of two types of distribution implemented in our version of the software, GaBi v. 4.3 (the other being equal distribution). Other distribution types (e.g. lognormal) can be used if found more appropriate, provided that such is possible in the modelling software employed. Uncertainties in the background processes were not considered as they were not known and the unit process database did not include them at the time of the study. Differences in impact scores between the compared systems were considered significant if the calculated 95% probability ranges of the impact scores from 1000 iterations did not overlap.

Although not deemed necessary in this case study, all other flows and parameters could be ascribed to standard deviations, supporting a more comprehensive uncertainty analysis. In such cases, standard deviations for each flow in foreground processes could be computed using the Pedigree matrix approach (Ciroth 2013). Uncertainties in the background processes should be considered based on standard deviations already assigned to flows in processes of the considered unit process database. Newer versions of the database offer such features.

The calculated probability ranges represent the modelled inventory uncertainty, but we did not account for covariation between processes that occur in some or all of the compared window systems (e.g. production of heat for the use stage), leading to correlations between uncertainties of those inventory processes. The employed modelling software (GaBi v. 4.3) did not allow taking this into account, but it would have reduced the uncertainty in comparison between the systems (see Sect. 11.4.2). Thus, in some cases there may be statistically significant difference in impact scores, even though that is not revealed by our analysis. On the other hand, uncertainties in background processes were also not considered in our case study, which would increase the uncertainty in the results and may, to some extent, counterbalance this effect. In addition, the characterisation and normalisation factors applied in the impact assessment are accompanied by uncertainties but these were not known to us and we were therefore unable to take them into account in our uncertainty analysis. They are expected to be equal to or higher than the inventory uncertainties.

39.3.3.5 Calculated LCI Results

Unit processes and life cycle inventories showing elementary flows for each window product system are documented in Annex, Sect. 39.4.4 (Tables 39.15, 39.16, 39.17, 39.18, 39.19, 39.20, 39.21, 39.22, 39.23, 39.24, 39.25, 39.26, 39.27, 39.28, 39.29, 39.30, 39.31, 39.32, 39.33 and 39.34).

39.3.4 Life Cycle Impact Assessment

Characterised results. The life cycle impacts are listed in characterised form in Table 39.10. All four window alternatives have impacts within the same order of magnitude. For most impact categories the impact scores follow the order W/C < W = W/ALU < PVC. Ranking of window systems normalised internally to the W window (equal to 100% of impact) is presented in Fig. 39.8. The W/C window has the lowest environmental impact in all 14 impact categories, while the PVC window system has the highest impact scores for 11 impact categories. For these 11 impact categories, the differences in impact scores between the W/C and PVC windows are statistically significant (the calculated 95% probability ranges of the impact scores do not overlap). The PVC window performs better in land use impacts with a significantly lower impact compared to the W and W/ALU window systems, but still slightly higher compared to the W/C window system. By contrast, the W window system performs significantly worse than the other window systems

Table 39.10 Characterised impacts and accompanying 95% probability ranges from Monte Carlo simulations for each window alternative

Impact category	Unit	Impact score (95% probability range)			
		W	W/ALU	PVC	W/C
Climate change	kg CO_2 eq.	1162 (1134–1189)	1158 (1129–1188)	1232 (1203–1260)	978 (933–1023)
Stratospheric ozone depletion	kg CFC-11 eq.	1.9e−5 (1.8e−5–1.9e.5)	1.6e−5 (1.5e−5–1.6e−5)	1.6e−5 (1.5e−5–1.6e−5)	1.4e−5 (1.4e−5–1.4e−5)
Photochemical ozone formation	kg NMVOC eq.	1.59 (1.55–1.63)	1.57 (1.53–1.61)	1.72 (1.67–1.76)	1.33 (1.26–1.4)
Terrestrial acidification	AE	2.00 (1.95–2.04)	2.00 (1.95–2.05)	2.31 (2.26–2.36)	1.67 (1.6–1.75)
Terrestrial eutrophication	AE	7.14 (6.94–7.35)	7.04 (6.83–7.24)	7.79 (7.56–8.02)	5.96 (5.61–6.32)
Freshwater eutrophication	kg P eq.	0.042 (0.041–0.043)	0.043 (0.041–0.044)	0.046 (0.044–0.047)	0.035 (0.033–0.037)
Marine eutrophication	kg N eq.	0.65 (0.63–0.67)	0.62 (0.60–0.64)	0.68 (0.66–0.7)	0.54 (0.51–0.57)
Freshwater ecotoxicity	CTU_e	2675 (2605–2745)	1755 (1706–1805)	1852 (1809–1895)	1545 (1461–1630)
Human toxicity (cancer)	CTU_h	2e−5 (1.9e−5–2e−5)	1.8e−5 (1.8e−5–1.9e−5)	3.4e−5 (3.3e−5–3.5e−5)	1.6e−5 (1.5e−5–1.7e−5)
Human toxicity (non-cancer)	CTU_h	1.5e−4 (1.5e−4–1.6e−4)	1.3e−4 (1.2e−4–1.3e−4)	1.3e−4 (1.3e−4–1.3e−4)	1.0e−4 (9.9e−5–1.1e−4)
Particulate matter formation	kg $PM_{2.5}$ eq. to air	0.085 (0.083–0.087)	0.082 (0.080–0.084)	0.116 (0.114–0.119)	0.070 (0.067–0.073)
Ionising radiation (human health)	kBq U235 eq.	7.69 (7.56–7.81)	7.99 (7.86–8.12)	8.63 (8.49–8.77)	6.26 (6.07–6.45)
Land use	kg C year	657 (646–668)	405 (399–410)	386 (384–387)	364 (351–377)
Resource depletion (minerals, fossils)	kg Sb eq.	0.0072 (0.0070–0.0073)	0.0074 (0.0072–0.0076)	0.0081 (0.0080–0.0083)	0.0063 (0.0060–0.0066)

W/ALU Wood/aluminium, *PVC* polyvinyl chloride, *W/C* wood/composite

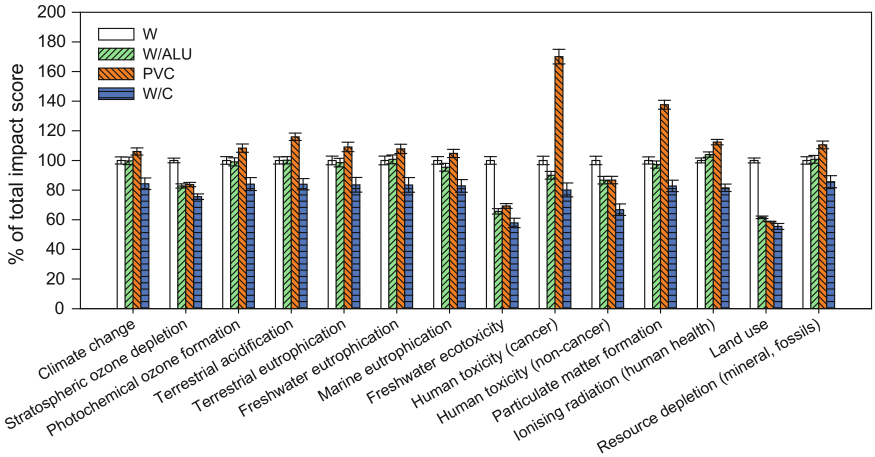


Fig. 39.8 Ranking of the four window options with impact scores scaled to those of the W window (equal to 100% of total impact). Whiskers represent inventory uncertainty stemming from uncertainty and variability in model parameters presented in Table 39.8

for the impact categories freshwater ecotoxicity, human toxicity (non-cancer), stratospheric ozone depletion, and land use. The W and W/ALU window systems rank as second or third for 10 out of 14 impact categories, but for these alternatives, differences between impact scores are only statistically significant in the ionising radiation impact category.

Normalised results. Figure 39.9 shows the normalised results. The common unit for indicator scores is person equivalents (pe) representing the annual impact of an average person in the European Union (EU27) in 2010. For nearly all the non-toxicity impact categories, like climate change, the life cycle impacts of the four windows correspond to approximately 10% of the total annual average impacts of an average EU27 citizen in the year 2010. Much smaller normalised impact scores are seen for stratospheric ozone depletion. Normalised results are somewhat higher for freshwater ecotoxicity and human toxicity impact categories (scoring up to 1 PE for cancer effects), but are smaller for respiratory effects and ionising radiation impacts on human health (around or below 0.1 PE). Normalised impact scores are the highest for human toxicity (cancer), equal to ca. 0.5 PE, but are small for land use (below 0.001 PE).

39.3.5 Interpretation

Before providing final recommendations to the commissioner of the study, it is necessary to interpret the results of the LCA.

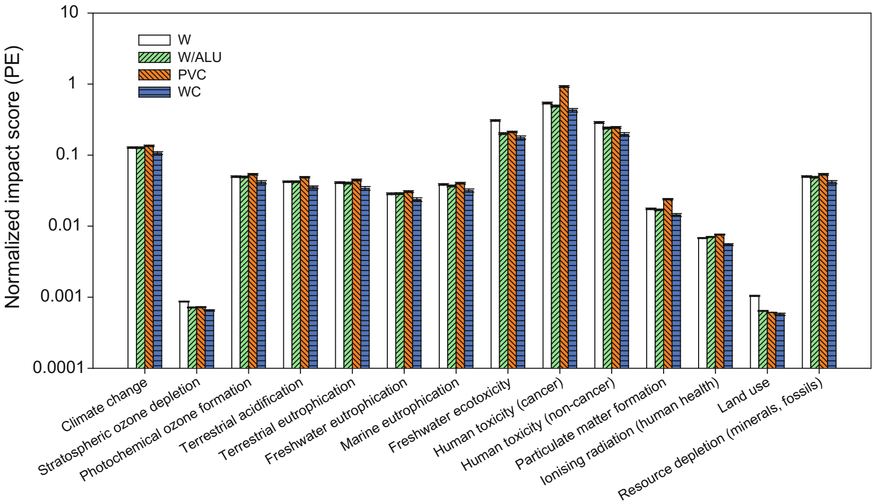


Fig. 39.9 Normalised impacts and accompanying 95% confidence intervals ($\log_{10}$-scale) in person equivalents (pe) for each window system (*W* wood, *W/ALU* wood/aluminium, *PVC* polyvinyl chloride, *W/C* wood/composite). Whiskers represent inventory uncertainty stemming from uncertainty and variability in model parameters presented in Table 39.8

39.3.5.1 Significant Issues

Process contribution analysis. To explain differences in window ranking and identify hot spots, a process contribution analysis was conducted, i.e. identifying the processes with the largest environmental burden.

Figure 39.10 shows that the main driver of environmental impacts is the production of residential heating to compensate for heat losses through the window. The contribution of this process to total impact is around 90% for climate change, freshwater eutrophication, or resource depletion, and is above 50% for most other impact categories (apart from ozone depletion and ionising radiation, where the contribution is smaller). This trend is consistent across all four window systems. Across all window systems, climate change impacts from the use stage due to combustion of fossil coal and natural gas, which constitute 25 and 31% of total Danish heating mix, respectively. The use of fossil fuels in the use stage is also the major driver of impacts related to depletion of resources. For other impact categories where the use stage is important (>50% of total impact score), however, the major driver of environmental impact is the use of other fuels like wood, straw and bio-waste. These processes are important for the impact categories terrestrial and freshwater eutrophication, and all the toxicity related impact categories.

Although the use stage is the main driver for the above-mentioned impact categories, for some impact categories the differences between window systems can sometimes be attributed to differences in material composition of the window. The manufacturing stage is important (>50% of total impacts) for impacts on

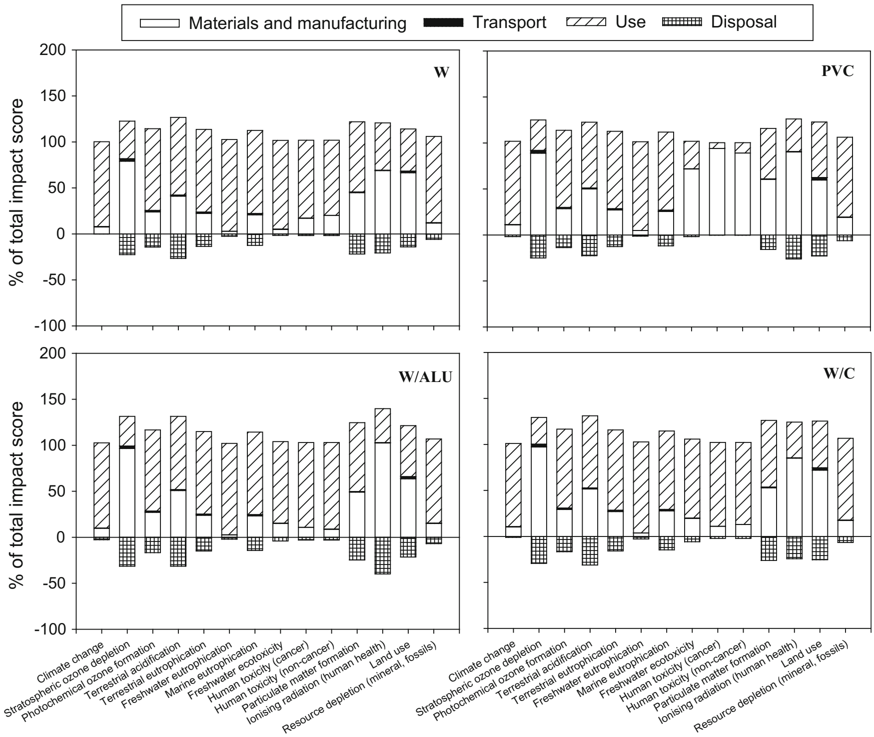


Fig. 39.10 Contribution of individual life cycle stages to total impact for each impact category for the four window systems (*W* wood, *W/ALU* wood/aluminium, *PVC* polyvinyl chloride, *W/C* wood/composite)

stratospheric ozone depletion, and ionising radiation (human health) across all windows, and for impacts on freshwater ecotoxicity and human toxicity. In addition, the manufacturing processes overall contribute to impacts on land use (around 40% of total impact) and to some extent also to the remaining impact categories (with contributions from 10 to 30%), reflecting that the materials used in the windows are considered part of the manufacturing stage. Substantial contribution to land use impacts in the W window is thus from the production of glue laminated timber. Impacts in these categories are also caused by production of alkyd paint (18 and 13% of total impact, respectively). In addition, the alkyd paint shows contribution of the same order of magnitude for four other impact categories, i.e. aquatic acidification, ionising radiation, ozone layer depletion and photochemical ozone formation. For the W/ALU window system, considerable impacts are caused by production of aluminium. This process contributes substantially to terrestrial acidification and stratospheric ozone depletion (20–23% of total impacts). Note that the introduction of aluminium has negative influence on the window performance in those impact categories that are determined by the use stage, because insulating properties are slightly worse than for the W window. Yet, the overall differences in impact scores are not statistically significant. Environmental impacts in the PVC window system in the manufacturing stage originate mainly from the PVC injection moulding process and production of steel. Injection moulding contributes substantially to impacts on human health (42 and 34% for carcinogens and non-carcinogens, respectively) while 94% of total impacts on mineral depletion is caused by the need for chromium; this, however, is not apparent in Fig. 39.10 because the resource depletion impact category is driven by the use of fossils. Given that insulation properties of the PVC window are not improved when PVC and steel are used in the window frame (they even decrease), the PVC window performs the worst among considered alternatives. An exception is an impact on land use, in which the PVC windows performs nearly as good as the best W/C window, which is mainly due to no use of wood in the PVC window. For the W/C window, the composite contributes to some extent (up to 12%) to some impact categories, but environmental benefits are obtained due to improved insulation properties. Across all windows, production of flat glass is a considerable contributor (>25% of total impact) to impacts on ionising radiation, stratospheric ozone depletion, and respiratory effects. In addition, silicone used as insulating material in the pane contributes substantially to ionising radiation and ozone layer depletion (15 and 32%, respectively).

The disposal stage is less important across all windows and impact categories, with contribution from 1 to 20% of the total impacts, depending on the impact category. Benefits are mainly due to recycling of materials, like aluminium in the W/ALU window system. Transportation is not seen as substantial for any impact category, irrespective of the window system.

Substance contribution analysis. To provide further insights into the causes of environmental impacts from the window product systems, the contribution analysis was also conducted at the level of elementary flows, identifying the individual substances that cause the largest environmental burden. The analysis was carried out for the W window system only, because for most impact categories the drivers of environmental impacts are expected to the same across windows. However, differences in contributing substances between the W window and the alternative design options are also discussed, when found important for the interpretation of results.

Climate change impacts are mainly driven by emissions of CO_2, which contributes to 99% of the total impacts. This contribution is mainly due to emissions from processes associated with generation of heat. Emissions of other substances from the generation of heat drive impact scores for several other impact categories. Potential impacts of photochemical ozone formation on human health are mainly due to emissions of nitrogen oxides (NO_x), which account for 95% of the total impact. Note, that the current implementation of characterisation factors into the modelling software employed omits potential contribution from unspecified emissions of non-methane volatile organic compounds (NMVOC), which are also reported in life cycle inventories (see Annex, Sect. 39.4.4, Table 39.34) and would be expected to contribute to photochemical ozone formation. Ammonia (NH_3), nitrogen oxides (NO_x) and sulphur dioxide (SO_2) are the substances that dominate the acidification and eutrophication impacts in terrestrial ecosystems, whereas eutrophication impacts in freshwater and marine ecosystems are mainly due to emissions of NO_x and phosphorus (P). By contrast, toxic impacts in freshwater ecosystems are dominated by emissions of metals (again, stemming mainly from processes associated with generation of heat), namely zinc (II) and copper (II).

For all window systems except the PVC system, the use stage is also the main contributor to the human health impact categories (carcinogens and non-carcinogens). Again, production of heat from incineration of fossil fuels and biomass, and the associated emissions of metals, are the major contributors to human health impacts; arsenic (V) and zinc (II) emitted to freshwater drive toxic impact scores for non-cancer effects, while chromium (VI) emitted to freshwater is the major driver of cancer effects. By contrast, for the PVC window, human health impacts (cancer and non-cancer effects) are mainly driven by substances associated with production of steel in the manufacturing stage. Potential impacts on depletion of resources also vary between windows when only mineral resources are considered (e.g. impacts of the PVC window are dominated by the need for chromium in production of the PVC window frame), but altogether (combining impact scores from depletion of fossils and minerals) this impact category is dominated by the depletion of fossils.

39.3.5.2 Sensitivity and Uncertainty Checks

The assumptions and choices that had to be made when modelling window systems can potentially influence conclusions from the study and they were systematically compiled in Table 39.14 of the Annex, Sect. 39.4.3. To determine the extent of this potential influence, we first identified individual parameters that are important for the results. Annex, Sect. 39.4.5, Tables 39.35, 39.36, 39.37, and 39.38 gives details of normalised sensitivity coefficients. Next, we compared the baseline and the two sensitivity scenarios with all uncertain parameters perturbed at once. Thereby, we found that many of the assumptions presented in Table 39.34 did not influence the results in terms of ranking or identification of hot spots to the extent that would change our conclusions.

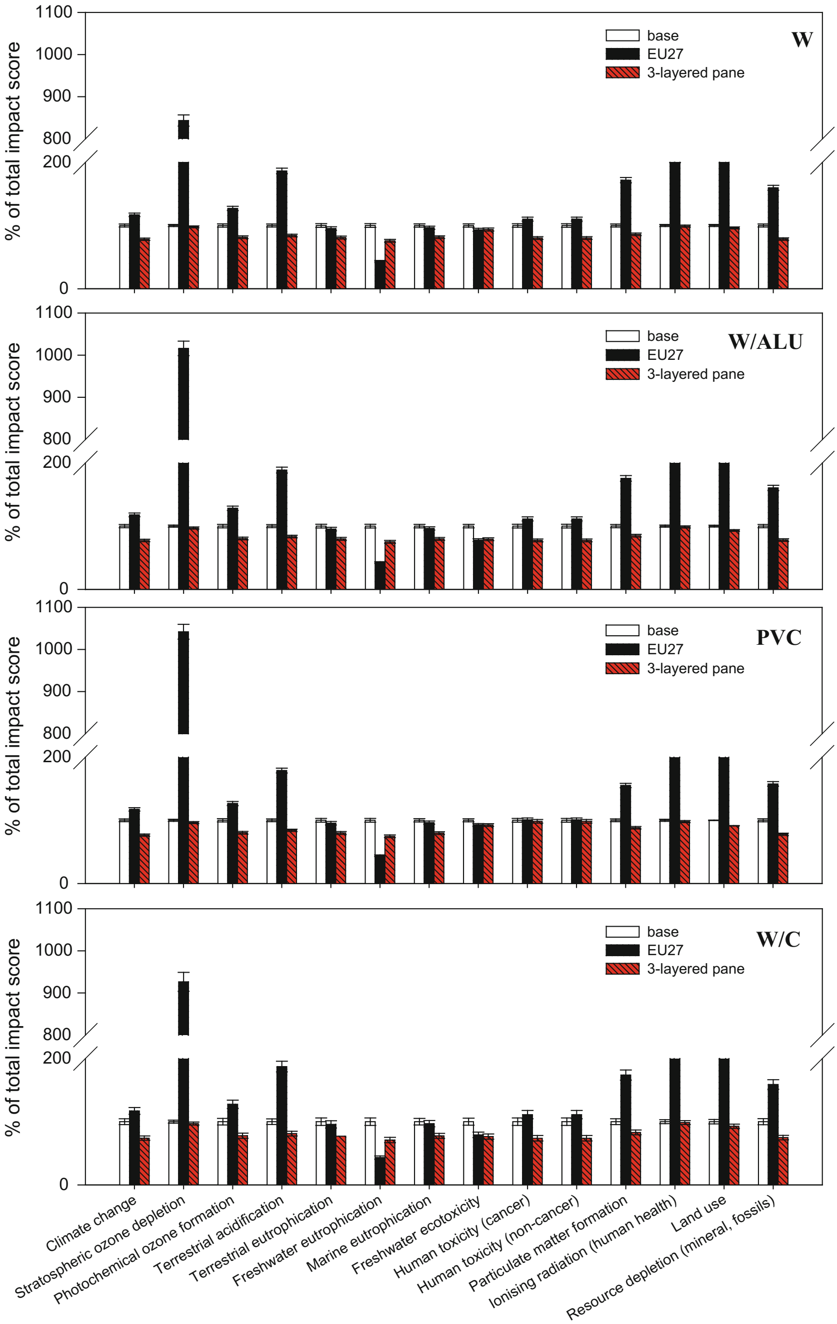
The influence of heat loss. The parameters involved in the modelling of the heat loss compensation are important because their uncertainty can potentially change the results of the comparative part of the LCA (which window performs best?) and the results of the weak point analysis (what are the most environmentally harmful parts of the product life cycle?). Such parameters are the modelled heat loss, the assumed heat mix, the LCI processes used to model the heat mix technologies and the relevant characterisation factors and normalisation references involved in the impact assessment. This was confirmed in sensitivity and uncertainty analyses; impact scores are the most sensitive to the *U*-value of the window, and furthermore this parameter is the dominant driver of difference in impact scores between the compared window systems. Indeed the differences in impact scores between W and

W/ALU windows are in most cases are not statistically significant when uncertainties in *U*-values are considered. The assumption about using average indoor and outdoor temperatures when calculating the heat loss was not tested in the sensitivity analysis but is not expected to change our conclusions about which window performs best as heat loss is a linear function of the temperature difference. Similarly, it would not change our conclusion about hot spots; if higher temperature difference was considered (e.g. corresponding to winter temperatures), the contribution of heat to total impact scores would increase due to higher demand for heat.

The influence of materials and production. Out of all assumptions in the materials and production stages, the most important one is about modelling of chromium steel and galvanised steel using the same processes (for chromium steel). This assumption may influence impact scores in human health (cancer effects) and freshwater ecotoxicity, where impact scores might be overestimated (because production of chromium steel is associated with toxic emissions of chromium (VI). In contrast, impacts in human health (non-cancer effects) are expected to increase if process for galvanised steel had been used, due to expected increase in emissions of toxic zinc (II). The contribution of electricity requirements in window manufacturing and disassembly is for most impact categories too small to influence our comparison, and the same is the case for assumptions on transportation distances in these life cycle stages. The exclusion of painting activity (but not production of paint) is also not expected to be important for the result, because impacts are mainly expected to stem from transportation of paint from retailer to the housing (which is small relative to other impacts from the window product systems).

The influence of disposal. Assumptions about incineration and landfilling processes for some materials are not expected to influence our conclusions, given that the contribution of disposal to total impact is relatively small (10–15%, depending on the impact category). The inclusion of landfilling of copper and zinc used in window frames could potentially influence impact scores for the toxicity-related impact categories (where both copper and zinc are characterised as very toxic), but the amounts of these metals is very small compared to emissions from production of heat in the use stage. For the same reason, omitting of disposal of wood preservative and acrylic binder in the window frame is not expected to change impact scores.

Comparison between the baseline and the two sensitivity scenarios. Figure 39.11 shows the comparison between the baseline scenario and the two sensitivity scenarios. When EU27 average heat mix is used (along with and EU27 electricity mix and EU27 average disposal scenarios), impact scores generally increase compared to the base scenario, apart from the three eutrophication impact categories, and freshwater ecotoxicity. This is because the European heating mix mainly relies on natural gas (57%), with smaller contribution from coal and biomass compared to the Danish mix. On the other hand, a larger proportion of natural gas and oil (57 and 21%, respectively), results in considerably higher impacts in other impact categories. We also tested a scenario where windowpanes are changed into 3-layered ones, causing a decrease in *U*-value thereby improving insulation properties of the window. The results show that additional environmental impacts from the extra layer of glass are generally compensated for by the reduced heat loss in the use stage, and the



W
W/ALU
PVC
W/C
base
EU27
3-layered pane
% of total impact score
0
200
800
900
1000
1100
Climate change
Stratospheric ozone depletion
Photochemical ozone formation
Terrestrial acidification
Terrestrial eutrophication
Freshwater eutrophication
Marine eutrophication
Freshwater ecotoxicity
Human toxicity (cancer)
Human toxicity (non-cancer)
Particulate matter formation
Ionising radiation (human health)
Land use
Resource depletion (mineral, fossils)

◂**Fig. 39.11** Comparison between the baseline and two sensitivity scenarios: (i) where EU27 electricity and heating mix and EU27 disposal options are used for each window, and (ii) where 3-layered windowpane used instead of 2-layered one. *W* wood, *W/ALU* wood/aluminium, *PVC* polyvinyl chloride, *W/C* wood/composite. Whiskers represent inventory uncertainty stemming from uncertainty and variability in model parameters presented in Table 39.8

overall life cycle impact are smaller compared to the base scenario by up to 20%. High increase for stratospheric ozone depletion is most likely an artefact related to the use of relatively old processes for generation of heat from natural gas and oil in the EU27 system, since ozone-depleting substances have been largely banned for at least a decade. Despite these differences in impact scores, the ranking of window options generally does not change irrespective of the analysed scenarios (Fig. 39.12). As whiskers do not overlap, the results can be considered statistically significant, although we repeat that neither were uncertainties in background processes considered (which would increase the overall inventory uncertainty), nor could correlation between uncertainties in processes that are the same be addressed (which would have an opposite effect). It is, however, clear that if the heat mix changes substantially within the lifetime of the window as a consequence of the decarbonisation of our energy systems, the hot spots may move from the use stage to manufacturing and end-of-life stages and this would change the ranking of the alternatives and also the recommendations for design of the windows.

Uncertainties in characterisation factors and sensitivity to LCIA method chosen. All characterisation factors in ILCD (just as in any other LCIA method) are associated with uncertainties, meaning that the contribution to impacts of different modelled elementary flows and processes (such as heating) display varying uncertainties across impact categories. Although the uncertainties in characterisation factors were not considered in this study (they are rarely even known today), we expect that the uncertainty in characterisation factors will result in lack of statistical significance of difference in impact scores for freshwater ecotoxicity and human toxicity across all four windows. These are the impact categories where the uncertainties in individual characterisation factors are the highest (up to a few orders of magnitude) (Rosenbaum et al. 2008).

Sensitivity of the results to the chosen LCIA methods is also not considered in this LCA report (because the results are for internal use only). Such a sensitivity analysis could reveal that window ranking generally does not change for most impact categories because it is a few processes, associated with the production of heat, that are driving the main environmental impacts and there is large difference in demand for heat between the compared windows. This is expected to be the case for climate change and acidifying and eutrophying emissions where the driving elementary flows are very similar between different impact assessment methods. However, this may not be the case for freshwater and human toxicity, where impact scores can be sensitive to the inclusion of one or few substances with high characterisation factors, depending on the method, as for these impact categories up to 12 orders of magnitude between characterisation factors are observed (Rosenbaum et al. 2008).

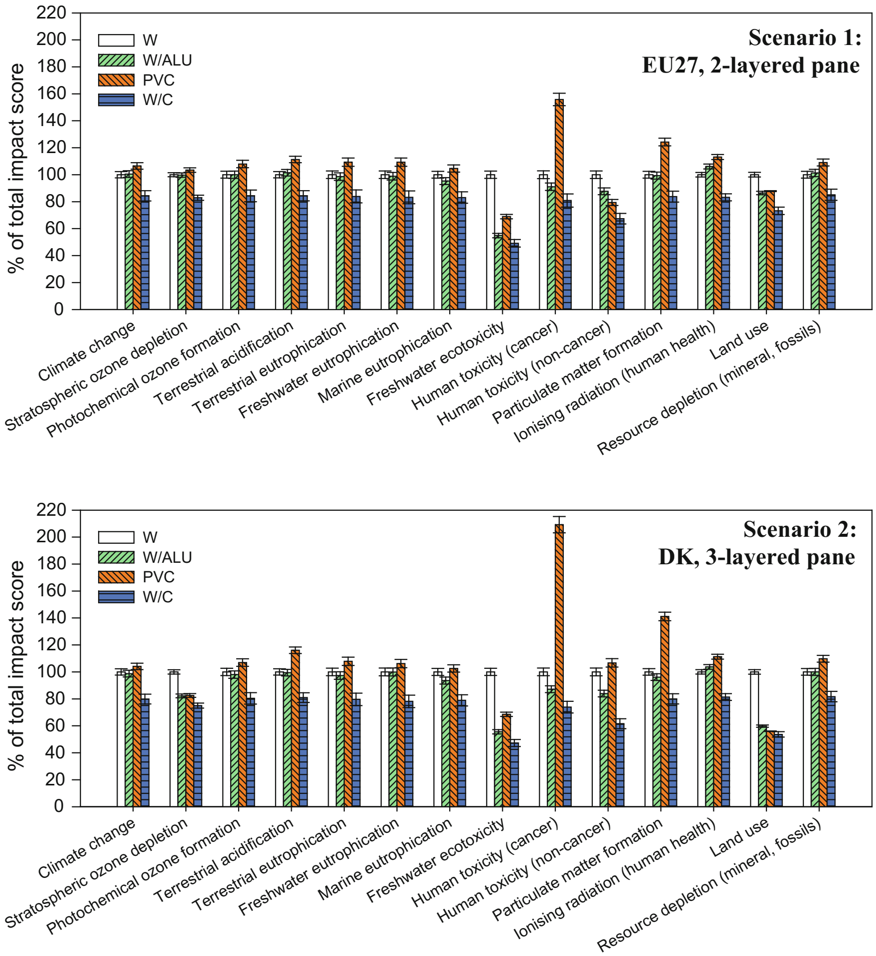


Fig. 39.12 Ranking of four window options where impact scores are scaled to those of W window (equal to 100% of total impact) for the two sensitivity scenarios presented in Fig. 39.11. *W* wood, *W/ALU* wood/aluminium, *PVC* polyvinyl chloride, *W/C* wood/composite. Whiskers represent inventory uncertainty stemming from uncertainty and variability in model parameters presented in Table 39.8

39.3.5.3 Completeness and Consistency Checks

Completeness check. The cut-off rules have been consistently applied across the whole life cycle for all four window alternatives in order to ensure the completeness of the study. However, two processes had to be left out when modelling life cycle inventories due either to difficulties in finding and approximating data, or they were not thought to be important initially. First, we did not include the coating of glass in the windowpane, where the current Nor-win technology uses nanomaterials because of limited information about input and output flows from nanomaterial production. This is expected to result in underestimation of human health and ecotoxicity impacts (some of the nanomaterials used by Nor-win are recognised to be toxic), and furthermore production of nanomaterials will to some extent contribute to total impact scores for other impact categories (Jolliet et al. 2014). We estimate that this contribution will not be larger than 1–2% of total impact scores for all impact categories, apart from the three toxicity-related impact categories where our rough estimate is 2.5–5% contribution. Second, we assumed no loss in material functionality in recycling of PVC (for metals and glass this assumption is expected to hold), nor did we assume material loss during recycling or production of the materials. Assuming that 10% increase in material is sufficient to cover this, total impact scores are expected to be higher by roughly 1–5%, depending on the impact category and contribution of manufacturing and disposal to total impacts. Finally, we did not include capital equipment for foreground processes. The contribution of capital equipment can be 10–30%, depending on the type of sector (Frischknecht et al. 2007). Given that contribution to overall impact from the materials and production stages is around 30% (although this number varies between windows and impact categories, see Fig. 39.10), the contribution of capital equipment is expected to be equal to ca. 10% to total impact score. Overall, we estimate that the calculated impact scores represent 75–85% of the actual total impacts.

Consistency check. The major source of inconsistency in data quality is the limited knowledge of performance parameters of the prototype W/C window (like the *U*-values), and we took this into account in the uncertainty and variability analysis. The major source of inconsistency in the applied life cycle impact assessment method is missing characterisation factors for some of the flows, due to incorrect implementation of life cycle impact assessment methods into the modelling software employed. This inconsistency is not expected to change impact scores to an extent that would change our conclusion about window ranking or major drivers of environmental impacts, since the majority of input and output flows are the same for all four windows (see Annex, Sect. 39.4.4, Table 39.34). Cut-off criteria were applied consistently across the four window product systems and the same processes were omitted. Other assumptions, methods and data (like the attributional principle with credits given to recycling, or the sources and quality of primary and secondary data) have also been applied consistently to all four window options.

39.3.6 Conclusions, Limitations and Recommendations

Conclusions:

I. The W/C window performs significantly better compared to its alternatives in all 14 impact categories. The W/C window is thus the preferable option from an environmental perspective.

II. The PVC window is the least preferred option, as it performs the worst in 11 out of 14 impact categories. This conclusion, however, might change if land use, freshwater ecotoxicity and human health (non-cancer) (where the W window performs significantly worse) are given a higher weight than the rest of the impact categories.

III. The overall environmental performance of the windows is mainly determined by the demand for heat to compensate for heat losses through the window during its use stage. This is true for nearly all impact categories. The U-value determines demand for heat, and can thus be considered a key environmental performance indicator of windows.

IV. In addition to processes for generation of heat, other environmental hotspots in the product systems are: production of timber and paint for the W window; the injection moulding process of PVC and production of steel in the PVC window.

V. The use of glass fiber based composite has some contribution (up to 12%) to total impacts, depending on the impact category, but cannot be considered a hotspot given that the composite substantially improves insulation properties causing an overall reduction in environmental impacts.

VI. Similarly, the use of 3-layered glass instead of 2-layered improves insulation properties resulting in an overall reduction in environmental impacts with the respective heating mix.

VII. The trade-off between impacts from the material used and the improved insulation properties that the material may give the window has to be considered when assessing environmental performance of windows.

Limitations:

The major limitations of the LCA are:

1. Our findings about major drivers of environmental impacts apply to windows where crystal glass is used in the panes with a relatively large (>0.6) visible light transmittance coefficient. They are not thought to be applicable for windows, which change their transparency in response to light intensity (e.g. photochromic windows) where the need for electricity to provide lighting indoor may become an important factor contributing to impacts in the use stage.
2. The disregard of changes in heat mix and heat demand in the future and potential development of more efficient heat supply technologies is another potential limitation. It is uncertain to what extent these will become effective within the time frame of the study (25–30 years). If such is the case, impacts from the manufacturing stage or disposal will become more important in the future (if there is no development of cleaner manufacturing and waste management technologies, which also is uncertain). They may change both the ranking of window alternatives and recommendations given to the commissioner. We expect, however, that in a 25–30 year time horizon the use stage will likely remain the most important contributor to total impacts from the window

product system, and efforts to design windows with low *U*-values should continue.

Recommendations:

Recommendations are given to the commissioner to support eco-design of the new window and greening of the whole value chain:

A. The design of windows to ensure better environmental performance should focus on optimising insulation properties of windows. This can be done by introducing a 3-layered pane, or improving the design of the frame. If the latter is considered, the choice of frame material is important and in each case where new frame material is used in the design of a frame we recommend evaluating (using tools like LCA) whether environmental benefits achieved by improved insulation properties are really sufficient to outweigh potential environmental burden from the use of novel materials. Indeed, if the heat mix changes substantially within the lifetime of the window this could potentially move the hotspots from the use stage to manufacturing and end-of-life stages in which case our recommendations for design of the windows might not hold.
B. Selection of new materials for frame design should consider functional properties of materials in a window design context, i.e. the focus should not be on selection of materials that perform environmentally best per unit mass of the materials, but on selection of materials that perform best considering insulation properties and the amount applied when used in the frame.
C. For the existing W-based windows, improvement potentials lie in selection of paints with lower environmental impact. For the paint applied for maintenance in the use stage, this may be outside the influence of the producer, because it is the window users who will select the type of paint. Our recommendation is to provide information to the users about recommended types of paint.
D. Finally, we recommend to phase-out the PVC window as the option with likely the highest environmental burden overall. If this is not possible, we recommend its redesign through the introduction of a 3-layered pane to improve its insulation properties. Further improvement potentials for the PVC window system lie mainly in selection of cleaner technology for production of PVC frame elements.

39.4 Annex (Public)

39.4.1 Life Cycle Impact Assessment Methods and Normalisation Factors

See Table 39.11.

Table 39.11 ILCD methods and normalisation factors for the impact categories considered in this study (EC-JRC 2011)

Impact category	Indicator	Unit	Model reference	Normalisation factor [unit/person/year]
Climate change	Radiative forcing as Global Warming Potential, 100 years horizon (GWP100)	kg CO_2 eq.	Baseline model of 100 years of the IPCC	9.10E+03
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11 eq.	Steady-state ODPs 1999 as in WMOassessment	2.16E−02
Human toxicity, cancer effects	Comparative Toxic Unit for humans	CTU_h	USEtox model (Rosenbaum et al. 2008)	3.68E−05
Human toxicity, non-cancer effects	Comparative Toxic Unit for humans	CTU_h	USEtox model (Rosenbaum et al. 2008)	5.32E−04
Particulate matter	Intake fraction for fine particles	kg $PM_{2.5}$ eq.	RiskPoll model (Rabl and Spadaro 2004) and Greco et al. (2007)	4.82E+00
Ionising radiation (human health)	Human exposure efficiency relative to U235	kg U235 eq.	Human health effect model as developed by Dreicer et al. (1995), Frischknecht et al. (2000)	1.13E+03
Photochemical ozone formation	Tropospheric ozone concentration increase	kg NMVOC eq.	LOTOS-EUROS (Van Zelm et al. 2008) as applied in ReCiPe	3.18E+01
Acidification	Accumulated Exceedance	mol H^+ eq.	Accumulated exceedance (Seppälä et al. 2006; Posch et al. 2008)	4.72E+01
Terrestrial eutrophication	Accumulated Exceedance	mol N eq.	Accumulated exceedance (Seppälä et al. 2006; Posch et al, 2008)	1.74E+02
Freshwater eutrophication	Residence time of nutrients in freshwater compartment (P)	kg P eq.	EUTREND model (Struijs et al. 2009) as implemented in ReCiPe	1.48E+00
Marine eutrophication	Residence time of nutrients in marine compartment (N)	kg N eq.	EUTREND model (Struijs et al. 2009) as implemented in ReCiPe	1.68E+01

(continued)

Table 39.11 (continued)

Impact category	Indicator	Unit	Model reference	Normalisation factor [unit/person/year]
Freshwater ecotoxicity	Comparative Toxic Unit for ecosystems	CTU_e	USEtox model (Rosenbaum et al. 2008)	8.71E+03
Land use	Soil Organic Matter	kg C deficit	Model based on Soil organic matter (SOM) (Milà i Canals et al. 2007)	6.30E+05
Water resource depletion	Water use related to local scarcity of water	kg water eq.	Model for water consumption as in Swiss Ecoscarcity (Frischknecht et al. 2006)	7.89E+01
Mineral fossil and renewable resource depletion	Scarcity	kg Sb eq.	CML 2002 (Guinée et al. 2002)	1.00E−01

Normalisation factors are for EU27 for the reference year 2010 as presented in Benini et al. (2014)

39.4.2 Bills of Materials and End-of-Life Options

See Tables 39.12 and 39.13.

Table 39.12 Amounts of materials (in kg) required to produce one window

Material	Window type			
	W	W/ALU	PVC	W/C
Window frame				
Heartwood	30	9.2	–	9.2
Polyvinyl chloride (PVC)	–	–	14	–
Composite	–	–	–	3.9
Aluminium	0.2	4.6	–	–
Galvanised steel	–	–	10	–
Chromium steel	0.5	1.2	5.1	1.2
Acrylic binder	0.168	0.056	–	0.056
Triethylene glycol	0.00427	0.00142	–	0.00142
Wood preservative	0.000525	0.000175	–	0.000175
Window pane				
Glass	56	56	56	56
Aluminium	0.4	0.4	0.4	0.4
Argon	0.06	0.06	0.06	0.06
Synthetic rubber (EDPM)	1	3.6	3.6	3.6
Silicone	1.4	1.4	1.4	1.4
Window packaging				
Polyethylene	0.2	0.2	0.2	0.2
Cardboard	1	1	1	1

Note, that the amounts are not scaled to the functional unit

Table 39.13 End-of-life options for window materials (percentage recycled/incinerated/landfilled) in Denmark and EU27 (given in brackets)

ID	Material	Window type			
		W	W/ALU	PVC	W/C
Window frame	Heartwood	DK: 90.5/9/0.5 EU27: 47/52/1		Not relevant	DK: 90.5/9/0.5 EU27: 47/52/1
	Polyvinyl chloride (PVC)	Not relevant	Not relevant	DK: 93/5/2 EU27: 76/17/7	Not relevant
	Composite	Not relevant	Not relevant	Not relevant	DK: 93/5/2 EU27: 76/17/7
	Aluminium	DK: 99.987/0.01/0.003 EU27: 99.885/0/0.115		Not relevant	Not relevant
	Steel (galvanised and chromium)	DK: 99.987/0.01/0.003 EU27: 99.885/0/0.115			
Window pane	Glass	99.853/0.018/0.129			
	Aluminium	DK: 99.987/0.01/0.003 EU27: 99.885/0/0.115			
	Synthetic rubber (EDPM)	99.39/0.604/0.06			
	Silicone	99.39/0.604/0.06			
Window packaging	Polyethylene	DK: 93/5/2 EU27: 76/17/7			
	Cardboard	DK: 99.32/0.59/0.09 EU27: 98.73/0.93/0.34			

Data from Eurostat (2016) for the reference year 2014. The options are based on the data retrieved from Eurostat for the categories: metal wastes (mixed ferrous and non-ferrous), glass wastes, paper and cardboard wastes, rubber wastes, plastic wastes, and wood wastes

39.4.3 List of Assumptions

See Table 39.14.

Table 39.14 List of assumptions

Assumptions	Window type			
	W	WA	PVC	W/C
Heat loss is based on the annual average temperatures indoor and outdoor in Denmark (7 and 17 °C, respectively), without considering the dynamics of temperature change during the year	x	x	x	x
Windows are only used in places covered by district heating	x	x	x	x
Processes for generation of heat from incinerating straw and incinerating of non-renewable waste in the Danish heat mix were modelled as incineration of bio-waste	x	x	x	x
Heat generation from biomass in the EU27 heat mix was modelled as incineration of bio-waste combined with combustion of wood pellets (50:50)	x	x	x	x
Energy consumption for window assembly covers all processes in the factory	x	x	x	x
Chromium steel and galvanised steel are modelled using the same process			x	
Painting activity of window frame is not modelled (but production of the paint is)	x			
Energy used in disassembly in end of life assumed equal to 1 MJ per 1 kg of window	x	x	x	x
PVC is 30% recycled, and 70% landfilled			x	
Disposal of wood preservative and acrylic binder is not modelled	x	x		
Incineration of Aluminium is modelled as municipal solid waste (MSW)	x	x	x	x
Landfilling of EDPM rubber is modelled as polypropylene (PP)	x	x	x	x
Incineration of silicone is modelled as incineration of plastic mixture	x	x	x	x
Argon from window pane is released to the atmosphere during window disassembly	x	x	x	x
Landfilling of copper and zinc in window frame is not modelled	x	x	x	x
Transportation distances are the same for all windows in the distribution stage	x	x	x	x
Transportation distances are the same for all windows in the end-of-life stage	x	x	x	x
Packaging is the same for all windows	x	x	x	x

Table 39.15 Inventory of the unit process "Use of window, U, MIOW"

Activity	W	W/ALU	PVC	W/C	Unit	Source/note
Output (main product or function)						
Window use, U, MIOW	0.5	0.5	0.67	0.5	p	Process output
Other outputs (waste to treatment)						
Disassembly of window, U, MIOW	0.5	0.5	0.67	0.5	p	See Table 39.19
DE: polyethylene, incineration (PE, Adapted)	1	1	1	1	kg	PlasticsEurope
DE: paper/cardboard, incineration (Adapted)	0.2	0.2	0.2	0.2	kg	PlasticsEurope
Inputs (materials, energy, resources)						
Assembly and packaging of window, U, MIOW	0.5	0.5	0.67	0.5	p	See Table 39.16
Production of window pane, 2-layered, U, MIOW	1	1	1	1	p	See Table 39.18
DK: heat mix	14,820	15,040	15,620	12,400	MJ	See Table 39.32
RER: alkyd paint, white, 60% in solvent, at plant	4.8	0	0	0	kg	ecoinvent, v. 2.2
GLO: truck PE <u-so> technology mix, diesel driven, Euro4, cargo |>34–40 t total cap. /27 t payload capacity	27.3	22.5	26.8	22.4	tkm	ecoinvent, v. 2.2
GLO: truck PE <u-so> technology mix, diesel driven, Euro3, cargo |>12–14 t total cap. /9.3 t payload capacity	9.1	7.5	8.9	7.5	tkm	ecoinvent, v. 2.2
RER: diesel, low-sulphur, at regional storage	0.703	0.581	0.69	0.803	kg	ecoinvent, v. 2.2

All outputs and inputs are scaled to the functional unit of the window systems, with windows used for 20 years

Table 39.16 Inventory of the unit process "Assembly and packaging of window, U, MIOW"

Activity	W	W/ALU	PVC	W/C	Unit	Source/note
Output (main product or function)						
Window assembled and packed, U, MIOW	1	1	1	1	p	Process output
Inputs (materials, energy, resources)						
Production of window frame, U, MIOW	1	1	1	1	p	See Table 39.17
Production of window pane, 2-layered, U, MIOW	1	1	1	1	p	See Table 39.18
DK: electricity, production mix DK	118	120	126	130	MJ	ecoinvent, v. 2.2
DK: heat mix	50	50	50	50	MJ	See Table 39.32
RER: corrugated board base paper, kraftliner, at plant	1	1	1	1	kg	ecoinvent, v. 2.2
RER: polyethylene film (PE-LD)	0.2	0.2	0.2	0.2	kg	PlasticsEurope

Note that inputs and outputs are not scaled to the functional unit of the window systems

39.4.4 Unit Processes and LCI Results

See Tables 39.15, 39.16, 39.17, 39.18, 39.19, 39.20, 39.21, 39.22, 39.23, 39.24, 39.25, 39.26, 39.27, 39.28, 39.29, 39.30, 39.31, 39.32, 39.33 and 39.34.

39.4.5 Normalised Sensitivity Coefficients

Normalised sensitivity coefficients were computed for the perturbance of the following parameters: amount of wood, aluminium, steel (W/C window only), and PVC (PVC window only) in the window frame, the amount of glass in the pane, amount of paint, electricity needed for assembly, *U*-value, and transportation distance from Nor-win to retailers. Thereby, we found that impact scores are most sensitive to *U*-value, and three other parameters (amount of wood and steel in the frame, and amount of glass in the pane). The normalised sensitivity coefficients for these four parameters are presented in Tables 39.35,39.36, 39.37 and 39.38.

39.5 Annex (Confidential)

No confidential data were used in the study.

Table 39.17 Inventory of the unit process "Production of window frame, U, MIOW"

Activity	W	W/ALU	PVC	W/C	Unit	Source/note
Output (main product or function)						
Window frame, U, MIOW	1	1	1	1	p	Process output
Inputs (materials, energy, resources)						
RER: glued laminated timber, outdoor use, at plant [benefication]	0.06	0.0184	0	0.0184	m^3	ecoinvent, v. 2.2
GLO: Truck PE <u-so> technology mix, diesel driven, Euro4, cargo |>34–40 t total cap. /27 t payload capacity	30	9.2	11.2	10.37	tkm	ecoinvent, v. 2.2
RER: diesel, low-sulphur, at regional storage	0.419	0.129	0.157	0.129	kg	ecoinvent, v. 2.2
RER: Aluminium extrusion profile <agg>	0.2	4.6	0	0	kg	ecoinvent, v. 2.2
RER: chromium steel product manufacturing, average metal working	0.5	1.2	15.1	1.2	kg	ecoinvent, v. 2.2
RER: triethylene glycol, at plant [organics]	0.00427	0.00131	0	0.00131	kg	ecoinvent, v. 2.2
RER: acrylic binder, 34% in H_2O, at plant [manufacturing] <agg>	0.168	0.0515	0	0.0515	kg	ecoinvent, v. 2.2
RER: wood preservative, organic salt, Cr-free, at plant [manufacturing] <agg>	0.000525	0.000161	0	0.000161	kg	ecoinvent, v. 2.2
DK: electricity, production mix DK	15	21	24	30	kg	ecoinvent, v. 2.2
RER: zinc coating, coils	0	0	0.151	0	m^2	ecoinvent, v. 2.2
RER: polyvinylchloride injection moulding part (PVC) PlasticsEurope	0	0	14	0	kg	PlasticsEurope
RER: glass fibre-reinforced plastic, polyamide, injection moulding, at plant	0	0	0	3.9	kg	ecoinvent, v. 2.2

Note that inputs and outputs are not scaled to the functional unit of the window systems

Table 39.18 Inventory of the unit process "Production of window pane, 2-layered, U, MIOW"

Activity	W	W/ALU	PVC	W/C	Unit	Source/note
Output (main product or function)						
Window pane, 2-layered, U, MIOW	1	1	1	1	p	Process output
Inputs (materials, energy, resources)						
REE: flat glass, coated, at plant	56	56	56	56	kg	ecoinvent, v. 2.2
GLO: truck PE <u-so> technology mix, diesel driven, Euro4, cargo |>34–40 t total cap. /27 t payload capacity	14	14	14	14	tkm	ecoinvent, v. 2.2
RER: diesel, low-sulphur, at regional storage	0.196	0.196	0.196	0.196	kg	ecoinvent, v. 2.2
RER: aluminium extrusion profile <agg>	0.4	0.4	0.4	0.4	kg	ecoinvent, v. 2.2
DE: polypropylene-EPDM granulate mix PE	1	1	1	1	kg	ecoinvent, v. 2.2
RER: silicone product, at plant	1.4	1.4	1.4	1.4	kg	ecoinvent, v. 2.2
DE: argon (gaseous)	0.06	0.06	0.06	0.06	kg	ecoinvent, v. 2.2
DK: electricity, production mix DK	5	5	5	5	MJ	ecoinvent, v. 2.2

Note that inputs and outputs are not scaled to the functional unit of the window systems

Table 39.19 Inventory of the unit process "Disassembly of window, U, MIOW"

Activity	W	W/ALU	PVC	W/C	Unit	Source/note
Output (main product or function)						
Window disassembled, U, MIOW	1	1	1	1	p	Process output
Other outputs (waste to treatment)						
Disposal of aluminium, U, MIOW	0.6	5	0.4	0.4	kg	See Table 39.20
Disposal of wood, U, MIOW	30.2	9.25	0	9.25	kg	See Table 39.26
Disposal of EPDM, U, MIOW						
Disposal of silicone, U, MIOW	1.4	1.4	1.4	1.4	kg	See Table 39.22
Disposal of steel, U, MIOW	0.5	1.2	15.1	1.2	kg	See Table 39.28
Disposal of polyvinyl chloride, U, MIOW	0	0	14	0	kg	See Table 39.30
Disposal of composite, U, MIOW	0	0	0	0	kg	See Table 39.31
Disposal of glass, U, MIOW	56	56	56	56	kg	See Table 39.23
Inputs (materials, energy, resources)						
DK: electricity, production mix DK	50	50	50	50	MJ	ecoinvent, v. 2.2
GLO: truck PE <u-so> technology mix, diesel driven, Euro4, cargo |>34–40 t total cap. /27 t payload capacity	4.485	3.695	4.4	3.67	tkm	ecoinvent, v. 2.2

Note that inputs and outputs are not scaled to the functional unit of the window systems

Table 39.20 Inventory of the unit process "Disposal of aluminium, U, MIOW"

Activity	W	W/ALU	PVC	W/C	Unit	Source/note
Output (main product or function)						
Aluminium recycling, U, MIOW	0.88	0.88	0.88	0.88	kg	See Table 39.21
Inputs (materials, energy, resources)						
Disposal of aluminium, U, MIOW	1	1	1	1	kg	Process input
CH: disposal, aluminium, 0% water, to municipal incineration	0	0	0	0	kg	ecoinvent, v. 2.2
CH: disposal, wood untreated, 20% water, to sanitary landfill	0.12	0.12	0.12	0.12	kg	ecoinvent, v. 2.2

Note that inputs and outputs are not scaled to the functional unit of the window systems

Table 39.21 Inventory of the unit process "Aluminium recycling, U, MIOW"

Activity	W	W/ALU	PVC	W/C	Unit	Source/note
Output (avoided product or function)						
DE: Aluminium ingot mix (Inverted)	0.97	0.97	0.97	0.97	kg	ecoinvent, v. 2.2; inverted process
Inputs (materials, energy, resources)						
Aluminium recycling, U, MIOW	1	1	1	1	kg	Process input

Note that inputs and outputs are not scaled to the functional unit of the window systems

Table 39.22 Inventory of the unit process "Disposal of EPDM, U, MIOW"

Activity	W	W/ALU	PVC	W/C	Unit	Source/note
Output (main product or function)						
RER: EPDM seal PE, p-agg	1	1	1	1	kg	ecoinvent, v. 2.2
Inputs (materials, energy, resources)						
Disposal of EPDM, U, MIOW	1	1	1	1	kg	Process input
CH: disposal, polypropylene, 15.9% water, to sanitary landfill	0	0	0	0	kg	ecoinvent, v. 2.2

Note that inputs and outputs are not scaled to the functional unit of the window systems

Table 39.23 Inventory of the unit process "Disposal of glass, U, MIOW"

Activity	W	W/ALU	PVC	W/C	Unit	Source/note
Inputs (materials, energy, resources)						
Disposal of glass, U, MIOW	1	1	1	1	kg	Process input
CH: disposal, building, glass pane (in burnable frame), to sorting plant, U, MIOW	1	1	1	1	kg	See Table 39.24

Note that inputs and outputs are not scaled to the functional unit of the window systems

Table 39.24 Inventory of the unit process "CH: disposal, building, glass pane (in burnable frame), to sorting plant, U, MIOW"

Activity	W	W/ALU	PVC	W/C	Unit	Source/note
Output (main product or function)						
CH: disposal, building, glass pane (in burnable frame), to sorting plant, U, MIOW	1	1	1	1	kg	Process output
Other outputs (avoided product or function)						
RER: flat glass, uncoated, at plant (inverted)	0.9	0.9	0.9	0.9	kg	ecoinvent, v. 2.2; inverted process
Inputs (materials, energy, resources)						
CH: disposal, building, glass pane (in burnable frame), to sorting plant	0.1	0.1	0.1	0.1	kg	ecoinvent, v. 2.2
CH: disposal, glass, 0% water, to inert material landfill	0	0	0	0	kg	ecoinvent, v. 2.2
RER: glass, cullets, sorted, at sorting plant	0.0071	0.0071	0.0071	0.0071	kg	ecoinvent, v. 2.2
RER: excavation, hydraulic digger	7.9E−06	7.9E−06	7.9E−06	7.9E−06	m^3	ecoinvent, v. 2.2
CH: electricity, low voltage, at grid	0.00014	0.00014	0.00014	0.00014	MJ	ecoinvent, v. 2.2
CH: sorting plant for construction waste	1.8E−12	1.8E−12	1.8E−12	1.8E−12	p	ecoinvent, v. 2.2

Note that inputs and outputs are not scaled to the functional unit of the window systems

Table 39.25 Inventory of the unit process "Disposal of silicone, U, MIOW"

Activity	W	W/ALU	PVC	W/C	Unit	Source/note
Inputs (materials, energy, resources)						
Disposal of silicone, U, MIOW	1	1	1	1	kg	Process input
CH: disposal, plastics, mixture, 15.3% water, to municipal incineration	1	1	1	1	kg	ecoinvent, v. 2.2

Note that inputs and outputs are not scaled to the functional unit of the window systems

Table 39.26 Inventory of the unit process "Disposal of wood, U, MIOW"

Activity	W	W/ALU	PVC	W/C	Unit	Source/note
Output (main product or function)						
Wood incineration, U, MIOW	1	1	1	1	kg	See Table 39.27
Inputs (materials, energy, resources)						
Disposal of wood, U, MIOW	1	1	1	1	kg	Process input

Note that inputs and outputs are not scaled to the functional unit of the window systems

Table 39.27 Inventory of the unit process "Wood incineration, U, MIOW"

Activity	W	W/ALU	PVC	W/C	Unit	Source/note
Output (main product or function)						
DE: wood (natural) in municipal waste incineration PE, p-agg	0.92	0.92	0.92	0.92	kg	PlasticsEurope
Inputs (materials, energy, resources)						
Wood incineration, U, MIOW	1	1	1	1	kg	Process input
CH: disposal, aluminium, 0% water, to municipal incineration	0.00022	0.00022	0.00022	0.00022	kg	ecoinvent, v. 2.2
CH: disposal, copper, 0% water, to municipal incineration	8.8E −05	8.8E −05	8.8E −05	8.8E −05	kg	ecoinvent, v. 2.2
CH: disposal, zinc in car shredder residue, 0% water, to municipal incineration	0.0041	0.0041	0.0041	0.0041	kg	ecoinvent, v. 2.2
CH: disposal, paint, 0% water, to municipal incineration	0.074	0.074	0.074	0.074	kg	ecoinvent, v. 2.2

Note that inputs and outputs are not scaled to the functional unit of the window systems

Table 39.28 Inventory of the unit process "Disposal of steel, U, MIOW"

Activity	W	W/ALU	PVC	W/C	Unit	Source/note
Output (main product or function)						
Steel recycling, U, MIOW	0.88	0.88	0.88	0.88	kg	See Table 39.29
Inputs (materials, energy, resources)						
Disposal of steel, U, MIOW	1	1	1	1	kg	Process input
CH: disposal, steel, 0% water, to municipal incineration	0	0	0	0	kg	ecoinvent, v. 2.2
CH: disposal, steel, 0% water, to inert material landfill	0.12	0.12	0.12	0.12	kg	ecoinvent, v. 2.2

Note that inputs and outputs are not scaled to the functional unit of the window systems

Table 39.29 Inventory of the unit process "Steel recycling, U, MIOW"

Activity	W	W/ALU	PVC	W/C	Unit	Source/note
Output (avoided product or function)						
DE: steel billet PE (inverted)	1	1	1	1	kg	PlasticsEurope, inverted process
Inputs (materials, energy, resources)						
Steel recycling, U, MIOW	1	1	1	1	kg	Process input

Note that inputs and outputs are not scaled to the functional unit of the window systems

Table 39.30 Inventory of the unit process "Disposal of polyvinyl chloride, U, MIOW"

Activity	W	W/ALU	PVC	W/C	Unit	Source/note
Output (main product or function)						
DE: polyvinyl chloride (PVC) PE, p-agg	0	0	0.7	0	kg	PE
Output (avoided product or function)						
DE: polyvinylchloride granulate mix (S-PVC) PE (inverted)	0	0	0.3	0	kg	PE, inverted process
Inputs (materials, energy, resources)						
Disposal of PVC, U, MIOW	0	0	1	0	kg	Process input
CH: disposal, polyvinyl chloride, 0.2% water, to sanitary landfill	0	0	0	0	kg	ecoinvent, v. 2.2

Note that inputs and outputs are not scaled to the functional unit of the window systems

Table 39.31 Inventory of the unit process "Disposal of composite, U, MIOW"

Activity	W	W/ALU	PVC	W/C	Unit	Source/note
Output (main product or function)						
RER: polyamide (PA) 6.6 GF ELCD/PE-Gabi p-agg	0	0	0	1	kg	PE
Inputs (materials, energy, resources)						
Disposal of composite, U, MIOW	0	0	0	1	kg	Process input

Note that inputs and outputs are not scaled to the functional unit of the window systems

Table 39.32 Inventory of the unit process "Heat, DK, SERF"

Activity	Value	Unit	Source/note
Output (main product or function)			
Heat, DK, SERF	1	MJ	Process output
Inputs (materials, energy, resources)			
CH: heat, wood pellets, at furnace 50 kW	0.0980	MJ	ecoinvent, v. 2.2
CH: heat, softwood chips from industry, at furnace 50 kW	0.1257	MJ	ecoinvent, v. 2.2
RER: heat, heavy fuel oil, at industrial furnace 1 MW	0.0235	MJ	ecoinvent, v. 2.2
RER: heat, natural gas, at industrial furnace >100 kW	0.2451	MJ	ecoinvent, v. 2.2
RER: heat, hard coal briquette, at stove 5–15 kW	0.2344	MJ	ecoinvent, v. 2.2
CH: heat, bio-waste, at waste incineration plant, allocation price	0.25	MJ	ecoinvent, v. 2.2
CH: heat, at cogen, biogas agricultural mix, allocation exergy	0.0195	MJ	ecoinvent, v. 2.2
CH: heat, at heat pump 30 kW, allocation exergy	0.0005	MJ	ecoinvent, v. 2.2
CH: heat, at solar + gas heating, tube collector, one-family house, combined system	0.0033	MJ	ecoinvent, v. 2.2

Note that inputs and outputs are not scaled to the functional unit of the window systems. The Danish heat mix is based on data from Energynet (2012). Processes for generation of heat from incinerating straw (0.077 MJ/MJ heat output) and incinerating of non-renewable waste (0.173 MJ/MJ heat output) are modelled as incineration of bio-waste

Table 39.33 Inventory of the unit process "Heat, EU27, MIOW"

Activity	Value	Unit	Source/note
Output (main product or function)			
Heat, EU27, MIOW	1	MJ	Process output
Inputs (materials, energy, resources)			
CH: heat, wood pellets, at furnace 50 kW	0.065	MJ	ecoinvent, v. 2.2
RER: heat, heavy fuel oil, at industrial furnace 1 MW	0.21	MJ	ecoinvent, v. 2.2
RER: heat, natural gas, at industrial furnace >100 kW	0.57	MJ	ecoinvent, v. 2.2
RER: heat, hard coal briquette, at stove 5–15 kW	0.09	MJ	ecoinvent, v. 2.2
CH: heat, bio-waste, at waste incineration plant, allocation price	0.065	MJ	ecoinvent, v. 2.2

Note that inputs and outputs are not scaled to the functional unit of the window systems. The EU27 heat mix is based on data from Conolly et al. (2012)

Table 39.34 LCI results (elementary flows for each window product system)

Substance	W	W/ALU	PVC	W/C
Emission to air				
1,1,1-trichloroethane	8.33E−11	1.22E−10	1.25E−10	6.49E−11
1-butanol	1.10E−12	5.10E−13	5.17E−13	4.57E−13
Acenaphthene	9.08E−11	8.27E−11	1.21E−10	8.30E−11
Acetaldehyde (ethanal)	3.62E−04	3.61E−04	3.70E−04	3.03E−04
Acetic acid	7.42E−04	6.45E−04	6.28E−04	5.81E−04
Acetone (dimethylcetone)	9.99E−05	1.02E−04	1.02E−04	8.42E−05
Acetonitrile	7.05E−08	6.35E−08	6.58E−08	6.21E−08
Acrolein	4.24E−08	3.26E−08	5.05E−08	2.75E−08
Acrylic acid	1.70E−08	7.91E−09	7.98E−09	7.09E−09
Aldehyde (unspecified)	1.61E−06	1.51E−06	3.28E−07	7.39E−06
Alkane (unspecified)	2.51E−02	4.60E−03	1.02E−02	3.97E−03
Alkene (unspecified)	8.42E−03	8.44E−03	8.73E−03	6.94E−03
Aluminium	1.56E−02	1.60E−02	1.80E−02	1.31E−02
Ammonia	6.25E−02	5.94E−02	7.32E−02	4.94E−02
Ammonium	7.86E−11	1.22E−10	2.85E−11	9.58E−11
Ammonium carbonate	9.60E−08	3.32E−08	4.78E−08	3.41E−08
Ammonium nitrate	4.55E−11	4.89E−11	3.64E−11	4.02E−11
Anthracene	1.98E−09	2.18E−09	2.11E−09	1.79E−09
Antimony	5.81E−06	7.24E−06	7.61E−06	6.32E−06
Aromatic hydrocarbons (unspecified)	9.28E−05	7.22E−05	3.22E−04	1.12E−04
Arsenic (+V)	3.53E−05	3.66E−05	4.83E−05	2.84E−05
Arsenic trioxide	2.27E−12	3.45E−12	2.41E−12	2.80E−12
Barium	7.00E−05	8.79E−05	7.78E−05	6.89E−05

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Benzal chloride	7.62E−15	3.04E−14	1.99E−14	5.85E−15
Benzaldehyde	1.29E−08	6.91E−09	1.59E−08	6.26E−09
Benzene	3.97E−03	3.91E−03	4.15E−03	3.32E−03
Benzo(a)anthracene	9.99E−10	1.10E−09	1.06E−09	9.00E−10
Benzo(a)pyrene	1.98E−06	2.21E−06	2.15E−06	1.59E−06
Benzo(ghi)perylene	8.91E−10	9.80E−10	9.46E−10	8.03E−10
Benzofluoranthene	1.78E−09	1.96E−09	1.89E−09	1.61E−09
Beryllium	3.57E−07	3.89E−07	4.30E−07	2.97E−07
Boron	1.26E−03	1.23E−03	1.40E−03	1.04E−03
Boron compounds (unspecified)	6.89E−04	7.32E−04	7.25E−04	5.80E−04
Boron trifluoride	1.42E−15	6.22E−16	6.24E−16	5.62E−16
Bromine	5.25E−04	5.37E−04	5.58E−04	4.38E−04
Butadiene	2.88E−10	2.12E−10	1.38E−10	1.78E−10
Butane	2.20E−03	2.28E−03	2.21E−03	1.95E−03
Butane (*n*-butane)	1.18E−03	1.22E−03	1.24E−03	9.94E−04
Butanone (methyl ethyl ketone)	3.06E−05	1.42E−05	1.44E−05	1.28E−05
Butene	1.94E−05	1.37E−05	1.75E−05	2.17E−05
Butylene glycol (butane diol)	3.53E−10	1.65E−10	1.67E−10	1.47E−10
butyrolactone	1.02E−10	4.76E−11	4.82E−11	4.27E−11
Cadmium (+II)	8.00E−06	7.30E−06	8.45E−06	6.08E−06
Carbon dioxide	8.39E+02	8.36E+02	8.90E+02	7.10E+02
Carbon dioxide (biotic)	2.47E+02	2.46E+02	2.56E+02	2.03E+02
Carbon dioxide (biotic)	4.94E−01	4.76E−01	4.69E−01	4.15E−01
Carbon dioxide, land transformation	2.68E−03	2.18E−03	3.00E−03	2.16E−03

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Carbon disulphide	3.22E−04	3.66E−04	3.59E−04	2.27E−04
Carbon monoxide	3.35E−01	3.22E−01	2.82E−01	2.57E−01
Carbon monoxide (biotic)	2.18E−01	2.18E−01	2.25E−01	1.79E−01
Carbon tetrachloride (tetrachloromethane)	5.56E−07	1.21E−07	1.66E−07	1.05E−07
Chloride (unspecified)	2.75E−05	5.97E−05	2.88E−05	2.75E−05
Chlorine	5.43E−04	5.27E−04	1.74E−03	4.37E−04
Chloromethane (methyl chloride)	5.16E−05	3.29E−05	3.29E−05	3.29E−05
Chlorosilane, trimethyl-	3.06E−10	1.42E−10	1.43E−10	1.27E−10
Chromium (+III)	1.20E−08	1.28E−08	1.26E−08	1.03E−08
Chromium (+VI)	2.93E−06	4.09E−06	4.94E−05	3.98E−06
Chromium (unspecified)	1.33E−04	1.77E−04	1.99E−03	1.72E−04
Chrysene	2.45E−09	2.70E−09	2.60E−09	2.21E−09
Cobalt	1.05E−05	1.05E−05	3.20E−05	9.73E−06
Copper (+II)	1.17E−04	1.08E−04	2.09E−04	9.33E−05
Cumene (isopropylbenzene)	2.52E−05	1.38E−05	1.64E−05	3.48E−05
Cyanide (unspecified)	3.03E−03	3.09E−03	3.25E−03	2.54E−03
Cycloalkanes (unspec.)	5.15E−06	2.46E−07	3.28E−07	3.89E−06
Cyclohexane (hexahydro benzene)	1.68E−07	1.95E−07	1.27E−07	1.39E−07
Dibenz(a)anthracene	5.55E−10	6.11E−10	5.90E−10	5.00E−10
Dichlorobenzene (o-DCB; 1,2-dichlorobenzene)	4.75E−08	2.21E−08	2.24E−08	1.98E−08
Dichloroethane (1,2-dichloroethane)	4.74E−06	3.03E−06	8.26E−06	3.55E−05
Dichloroethane (ethylene dichloride)	1.01E−09	1.01E−09	4.53E−04	1.01E−09
Dichloromethane (methylene chloride)	2.79E−09	2.73E−09	2.93E−06	9.60E−09
Diethylamine	1.97E−15	3.04E−15	7.13E−16	2.40E−15

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Dioxins (unspec.)	1.95E−14	2.89E−14	2.74E−09	2.46E−14
Dust (>PM_{10})	2.68E−01	2.57E−01	2.89E−01	2.19E−01
Dust (PM_{10})	2.76E−03	3.21E−03	1.98E−02	2.40E−03
Dust ($PM_{2,5}$–PM_{10})	2.45E−02	1.66E−02	3.42E−02	1.83E−02
Dust ($PM_{2.5}$)	6.70E−02	6.42E−02	8.51E−02	5.52E−02
Dust (unspecified)	3.19E−02	4.03E−02	3.41E−02	2.71E−02
Emissions to air	4.94E+03	5.01E+03	5.08E+03	4.16E+03
Ethane	6.12E−03	6.76E−03	6.37E−03	5.71E−03
Ethanol	1.79E−04	1.92E−04	1.90E−04	1.57E−04
Ethene (ethylene)	2.36E−04	1.75E−04	4.25E−04	1.71E−04
Ethine (acetylene)	1.36E−04	1.25E−04	1.37E−04	1.24E−04
Ethyl benzene	7.63E−04	8.04E−04	7.95E−04	6.36E−04
Ethyl cellulose	6.19E−08	2.87E−08	2.90E−08	2.57E−08
Ethylene acetate (ethyl acetate)	3.06E−05	1.42E−05	1.44E−05	1.28E−05
Ethylene oxide	4.42E−07	2.31E−07	2.30E−07	4.25E−07
Ethylenediamine	6.52E−10	6.50E−10	6.58E−10	6.50E−10
Exhaust	3.54E+03	3.58E+03	3.61E+03	2.97E+03
Fluoranthene	6.46E−09	7.11E−09	6.86E−09	5.82E−09
Fluorene	2.05E−08	2.26E−08	2.18E−08	1.85E−08
Fluoride	6.62E−05	3.09E−04	5.60E−05	5.62E−05
Fluorine	1.26E−04	1.25E−04	1.36E−04	1.08E−04
Formaldehyde (methanal)	2.81E−03	2.34E−03	2.20E−03	1.97E−03
Formic acid (methane acid)	5.10E−07	4.42E−07	4.58E−07	4.31E−07
Furan	1.34E−07	1.21E−07	1.25E−07	1.18E−07

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Group NMVOC to air	2.74E−01	2.30E−01	2.40E−01	2.05E−01
Group PAH to air	5.33E−05	7.66E−05	5.71E−05	4.82E−05
Halogenated hydrocarbons (unspecified)	1.93E−07	1.93E−07	1.39E−04	1.93E−07
Halogenated organic emissions to air	4.40E−04	4.85E−04	2.23E−03	4.06E−04
Halon (1211)	5.52E−07	4.23E−07	5.58E−07	3.93E−07
Halon (1301)	5.67E−07	4.17E−07	5.54E−07	3.69E−07
Heavy metals to air	2.45E−03	2.73E−03	5.25E−03	2.07E−03
Heavy metals to air (unspecified)	7.49E−10	6.98E−10	−2.10E−08	2.78E−10
Helium	5.92E−05	4.77E−05	5.33E−05	4.14E−05
Heptane (isomers)	2.05E−04	1.56E−04	1.73E−04	1.38E−04
Hexachlorobenzene (Perchlorobenzene)	8.38E−07	8.51E−07	9.04E−07	7.00E−07
Hexafluorosilicates	1.22E−06	9.74E−07	1.19E−06	9.21E−07
Hexamethylene diamine (HMDA)	4.53E−12	6.95E−12	2.48E−12	5.52E−12
Hexane (isomers)	1.21E−03	4.15E−04	4.93E−04	3.79E−04
Hydrocarbons (unspecified)	9.01E−04	9.01E−04	3.36E−02	9.01E−04
Hydrocarbons, aromatic	1.33E−04	1.10E−04	1.88E−04	9.60E−05
Hydrocarbons, chlorinated	3.25E−04	3.09E−04	2.17E−04	2.45E−04
Hydrogen	2.51E−03	2.17E−03	4.33E−02	2.33E−03
Hydrogen arsenic (arsine)	1.89E−10	2.86E−10	2.00E−10	2.32E−10
Hydrogen bromine (hydrobromic acid)	1.47E−08	1.54E−08	8.83E−09	1.91E−08
Hydrogen chloride	7.40E−03	8.06E−03	1.83E−02	6.71E−03
Hydrogen cyanide (prussic acid)	4.41E−08	7.64E−08	−1.41E−07	2.97E−08
Hydrogen fluoride	1.72E−03	1.98E−03	2.08E−03	1.51E−03
Hydrogen iodide	1.52E−11	1.58E−11	8.71E−12	2.01E−11

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Hydrogen phosphorous	5.23E−09	2.82E−08	4.18E−09	4.18E−09
Hydrogen sulphide	−2.82E−05	−2.63E−03	1.71E−04	−2.80E−05
Indeno(1,2,3-cd)pyrene	6.63E−10	7.29E−10	7.04E−10	5.97E−10
Inorganic emissions to air	1.39E+03	1.42E+03	1.47E+03	1.18E+03
Iodine	1.27E−05	9.96E−06	1.65E−05	9.97E−06
Iron	1.05E−04	9.55E−05	2.77E−04	8.44E−05
Isocyanide acid	1.20E−03	3.67E−04	5.38E−07	3.67E−04
Isoprene	6.21E−09	5.59E−09	5.80E−09	5.47E−09
Lanthanides	1.39E−10	1.63E−10	1.09E−10	1.18E−10
Lead (+II)	1.62E−04	1.74E−04	2.80E−04	1.31E−04
Lead dioxide	5.85E−12	9.28E−12	4.08E−12	5.13E−12
Magnesium	2.28E−10	8.97E−10	5.89E−10	1.75E−10
Manganese (+II)	4.58E−04	4.57E−04	4.96E−04	3.77E−04
Mercaptan (unspecified)	5.80E−07	1.09E−06	2.97E−05	9.46E−07
Mercury (+II)	1.66E−05	1.62E−05	2.24E−05	1.32E−05
Metals (unspecified)	7.82E−06	1.81E−05	3.41E−04	1.81E−05
Methacrylate	1.93E−08	8.98E−09	9.05E−09	8.04E−09
Methane	1.86E+00	1.89E+00	2.25E+00	1.63E+00
Methane (biotic)	9.46E−03	9.04E−03	1.08E−02	8.00E−03
Methanol	7.97E−04	4.35E−04	4.05E−04	4.19E−04
Methyl amine	3.69E−11	1.72E−11	1.74E−11	1.54E−11
Methyl borate	6.53E−15	3.03E−15	3.06E−15	2.71E−15
Methyl bromide	1.65E−15	6.86E−15	4.46E−15	1.26E−15
Methyl formate	7.50E−11	3.48E−11	3.51E−11	3.12E−11

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Methyl tert-butylether	1.94E−06	1.00E−06	6.17E−07	9.31E−07
Molybdenum	1.86E−06	1.63E−06	2.03E−06	1.43E−06
Monoethanolamine	1.13E−05	1.07E−05	1.09E−05	1.07E−05
Naphthalene	2.08E−07	2.29E−07	2.21E−07	1.88E−07
Nickel (+II)	8.04E−05	6.70E−05	1.04E−04	5.96E−05
Nitrate	1.05E−07	1.13E−07	1.59E−07	8.70E−08
Nitrogen (atmospheric nitrogen)	3.42E−02	3.74E−02	3.24E−02	2.93E−02
Nitrogen dioxide	9.95E−04	9.95E−04	7.04E−02	9.95E−04
Nitrogen monoxide	1.99E−09	2.17E−09	2.07E−09	1.72E−09
Nitrogen oxides	1.48E+00	1.46E+00	1.53E+00	1.24E+00
Nitrous oxide (laughing gas)	9.64E−02	9.35E−02	9.73E−02	7.88E−02
NMVOC (unspecified)	2.01E−01	1.77E−01	1.79E−01	1.60E−01
Octane	6.50E−06	1.14E−05	8.01E−06	9.83E−06
Organic chlorine compounds	6.61E−10	6.63E−10	9.66E−05	6.59E−10
Organic emissions to air (group VOC)	2.15E+00	2.13E+00	2.54E+00	1.85E+00
Other emissions to air	3.54E+03	3.59E+03	3.61E+03	2.98E+03
Oxygen	2.06E−02	2.45E−02	1.96E−02	1.87E−02
Ozone	2.05E−04	1.54E−04	2.46E−04	1.49E−04
Palladium	−1.13E−14	−6.16E−14	−9.03E−15	−9.01E−15
Particles to air	4.09E−01	3.97E−01	4.80E−01	3.35E−01
Pentachlorobenzene	2.05E−06	2.09E−06	2.18E−06	1.71E−06
Pentachlorophenol (PCP)	4.09E−07	3.76E−07	4.67E−07	3.32E−07
Pentane (*n*-pentane)	4.00E−03	3.84E−03	4.10E−03	3.23E−03
Phenanthrene	6.55E−08	7.20E−08	6.95E−08	5.90E−08

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Phenol (hydroxy benzene)	4.46E−06	3.80E−06	6.54E−06	1.25E−05
Phosphorus	1.69E−03	1.71E−03	1.78E−03	1.41E−03
Platinum	1.70E−11	1.58E−11	2.28E−11	1.64E−11
Polychlorinated biphenyls (PCB unspecified)	3.81E−08	3.31E−08	6.03E−08	2.97E−08
Polychlorinated dibenzo-*p*-dioxins (2,3,7,8—TCDD)	6.50E−09	6.63E−09	6.91E−09	5.44E−09
Polycyclic aromatic hydrocarbons (PAH)	5.11E−05	7.41E−05	5.46E−05	4.63E−05
Propane	8.26E−03	9.58E−03	8.81E−03	8.00E−03
Propanol (iso-propanol; isopropanol)	6.59E−06	3.06E−06	3.08E−06	2.74E−06
Propene (propylene)	1.27E−04	1.12E−04	1.46E−04	1.19E−04
Propionaldehyde	1.32E−08	7.18E−09	1.64E−08	6.53E−09
Propionic acid (propane acid)	5.10E−06	4.23E−06	5.75E−06	3.82E−06
Propylene oxide	1.40E−06	1.12E−06	1.15E−06	1.00E−06
R 11 (trichlorofluoromethane)	4.22E−07	1.16E−06	2.11E−07	5.00E−07
R 113 (trichlorofluoroethane)	8.09E−10	3.76E−10	3.79E−10	3.36E−10
R 114 (dichlorotetrafluoroethane)	7.19E−07	1.42E−06	5.70E−07	7.41E−07
R 116 (hexafluoroethane)	2.44E−06	8.08E−06	2.11E−06	1.88E−06
R 12 (dichlorodifluoromethane)	3.98E−06	2.73E−06	2.72E−06	3.85E−06
R 13 (chlorotrifluoromethane)	5.70E−08	1.57E−07	2.85E−08	6.76E−08
R 134a (tetrafluoroethane)	2.07E−08	1.57E−08	2.29E−08	1.55E−08
R 152a (difluoroethane)	1.91E−08	1.51E−08	2.42E−08	1.51E−08
R 21 (dichlorofluoromethane)	1.21E−11	6.81E−12	7.00E−12	6.56E−12
R 22 (chlorodifluoromethane)	2.19E−06	1.85E−06	2.17E−06	1.59E−06
R 23 (trifluoromethane)	3.84E−09	2.17E−09	2.23E−09	2.09E−09
Radioactive emissions to air	5.07E−06	4.93E−06	6.27E−06	4.09E−06

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Rhodium	−1.09E−14	−5.95E−14	−8.71E−15	−8.69E−15
Scandium	1.90E−08	1.69E−08	6.06E−08	1.52E−08
Selenium	7.02E−05	7.31E−05	7.47E−05	5.87E−05
Silicium tetrafluoride	2.69E−08	1.76E−08	1.80E−08	1.72E−08
Silver	3.57E−09	2.90E−09	9.33E−09	2.93E−09
Sodium chlorate	1.21E−07	1.10E−07	1.16E−07	1.05E−07
Sodium dichromate	3.44E−07	3.37E−07	4.66E−07	2.83E−07
Sodium formate	4.91E−07	4.87E−07	4.91E−07	4.86E−07
Sodium hydro	1.71E−07	7.94E−08	8.02E−08	7.11E−08
Steam	3.05E+02	3.34E+02	3.22E+02	2.62E+02
Strontium	5.10E−06	4.19E−06	1.19E−05	3.95E−06
Styrene	5.06E−07	4.23E−07	7.34E−07	5.74E−07
Sulphate	1.99E−10	2.91E−10	2.99E−10	1.55E−10
Sulphur dioxide	5.44E−01	5.62E−01	6.95E−01	4.62E−01
Sulphur hexafluoride	2.85E−06	2.06E−06	3.11E−06	2.03E−06
Sulphuric acid	1.15E−07	1.56E−07	6.24E−08	8.50E−08
Tellurium	1.60E−09	1.70E−09	1.68E−09	1.37E−09
Terpenes	5.87E−08	5.29E−08	5.49E−08	5.17E−08
Tetrachloroethene (perchloroethylene)	1.88E−05	4.51E−05	7.56E−04	4.51E−05
Tetrafluoromethane	2.14E−05	7.25E−05	1.88E−05	1.67E−05
Thallium	1.21E−07	1.15E−07	7.95E−08	9.26E−08
Thorium (Th230)	4.10E−09	3.44E−09	5.17E−09	3.05E−09
Thorium (Th232)	6.85E−07	5.43E−07	1.18E−06	5.28E−07
Tin (+IV)	9.88E−05	1.01E−04	1.12E−04	9.27E−05

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Tin oxide	5.09E−13	8.08E−13	3.55E−13	4.46E−13
Titanium	5.62E−06	5.06E−06	1.80E−05	4.58E−06
Toluene (methyl benzene)	2.23E−03	2.22E−03	2.32E−03	1.83E−03
Trichloromethane (chloroform)	3.33E−08	1.98E−08	2.40E−08	1.88E−08
Trimethylbenzene	4.96E−12	7.87E−12	3.46E−12	4.34E−12
Uranium (total)	4.38E−06	4.38E−06	5.09E−06	3.56E−06
Used air	7.05E+00	1.56E+01	−1.50E+00	1.55E+01
Vanadium (+III)	1.14E−04	1.14E−04	1.15E−04	8.98E−05
Vinyl chloride (VCM; chloroethene)	2.91E−06	2.07E−06	5.86E−04	1.84E−05
VOC (unspecified)	3.92E−05	4.23E−05	6.96E−04	4.07E−05
Wood (dust)	1.88E−10	2.98E−10	1.31E−10	1.65E−10
Xylene (dimethyl benzene)	3.37E−03	3.51E−03	3.57E−03	2.82E−03
Xylene (meta-xylene; 1,3-dimethylbenzene)	2.97E−04	2.96E−04	3.07E−04	2.44E−04
Zinc (+II)	1.02E−03	1.27E−03	1.40E−03	8.37E−04
Zinc oxide	1.02E−12	1.62E−12	7.10E−13	8.92E−13
Zinc sulphate	4.54E−09	6.99E−09	4.81E−09	5.68E−09
Emissions to freshwater				
1,2-dibromoethane	3.95E−11	4.57E−11	2.97E−11	3.27E−11
1-butanol	1.11E−07	5.16E−08	5.22E−08	4.63E−08
Acenaphthene	4.75E−09	4.54E−09	4.29E−09	3.98E−09
Acenaphthylene	6.41E−10	9.52E−10	6.95E−10	8.26E−10
Acetaldehyde (Ethanal)	2.03E−07	9.43E−08	9.53E−08	8.45E−08
Acetic acid	2.31E−05	1.56E−05	9.00E−06	1.72E−05
Acetone (dimethylcetone)	1.10E−10	4.32E−10	2.84E−10	8.43E−11

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Acid (calculated as H +)	9.13E−05	4.21E−04	2.07E−04	1.18E−04
Acrylic acid	4.03E−08	1.87E−08	1.89E−08	1.68E−08
Acrylonitrile	2.66E−10	4.08E−10	1.45E−10	3.24E−10
Adsorbable organic halogen compounds (AOX)	3.90E−05	3.41E−05	2.47E−05	3.23E−05
Alkane (unspecified)	7.90E−05	5.50E−05	6.46E−05	4.90E−05
Alkene (unspecified)	7.29E−06	5.08E−06	5.96E−06	4.52E−06
Aluminium (+III)	6.72E+00	7.10E+00	7.12E+00	5.66E+00
Aluminium (+III)	1.82E−03	2.45E−03	7.38E−03	1.80E−03
Ammonia	4.43E−07	4.70E−07	1.16E−07	3.68E−07
Ammonium/ammonia	1.64E−05	1.25E−05	2.79E−03	1.34E−05
Ammonium/ammonia	1.79E−03	1.67E−03	3.10E−03	5.15E−03
Analytical measures to freshwater	4.23E+00	3.85E+00	5.21E+00	3.25E+00
Anthracene	1.56E−09	2.98E−09	1.87E−09	2.49E−09
Antimony	3.82E−05	1.99E−05	6.67E−05	7.28E−05
Antimony	2.16E−05	1.15E−05	2.03E−05	4.03E−05
Aromatic hydrocarbons (unspecified)	3.21E−04	2.25E−04	2.78E−04	2.00E−04
Arsenic (+V)	9.48E−04	9.66E−04	1.02E−03	7.93E−04
Arsenic (+V)	8.62E−04	8.71E−04	9.34E−04	7.20E−04
Barium	4.92E−04	4.00E−04	2.07E−03	4.01E−04
Barium	5.56E−04	4.25E−04	9.33E−04	3.73E−04
Benzene	9.88E−05	6.16E−05	7.41E−05	1.31E−04
Benzo(a)anthracene	1.27E−10	2.53E−10	1.62E−10	2.24E−10
Benzofluoranthene	5.13E−11	1.14E−10	7.24E−11	1.07E−10
Beryllium	3.44E−06	2.66E−06	7.92E−06	2.64E−06

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Beryllium	1.12E−08	1.19E−08	1.43E−08	9.18E−09
Biological oxygen demand (BOD)	1.43E−01	9.34E−02	1.17E−01	8.63E−02
Boron	6.11E−03	6.12E−03	6.58E−03	5.10E−03
Boron	2.23E−03	2.28E−03	2.38E−03	1.88E−03
Bromate	6.12E−04	5.08E−04	5.42E−04	4.18E−04
Bromine	9.04E−04	9.18E−04	1.44E−03	7.70E−04
Bromine	4.69E−03	4.63E−03	4.93E−03	3.89E−03
Butene	1.86E−07	2.98E−07	3.77E−06	2.31E−05
Butylene glycol (butane diol)	1.41E−10	6.58E−11	6.67E−11	5.90E−11
butyrolactone	2.45E−10	1.14E−10	1.16E−10	1.02E−10
Cadmium (+II)	2.15E−05	2.16E−05	4.16E−05	1.81E−05
Cadmium (+II)	1.19E−05	1.22E−05	1.17E−05	9.81E−06
Calcium (+II)	1.74E+01	1.78E+01	1.86E+01	1.46E+01
Calcium (+II)	2.90E−01	2.90E−01	2.71E−01	2.46E−01
Carbon, organically bound	3.78E−05	6.39E−05	4.17E−05	5.21E−05
Carbonate	4.50E−04	6.78E−04	7.71E−03	7.18E−04
Cesium	6.08E−07	4.23E−07	4.97E−07	3.77E−07
Chemical oxygen demand (COD)	3.71E+00	3.61E+00	4.79E+00	3.00E+00
Chlorate	4.68E−03	3.88E−03	6.37E−03	3.21E−03
Chloride	9.62E−02	8.47E−02	3.11E+00	7.03E−02
Chloride	7.65E+00	7.62E+00	8.42E+00	6.34E+00
Chlorinated hydrocarbons (unspecified)	8.88E−08	2.13E−07	3.58E−06	2.13E−07
Chlorine (dissolved)	5.85E−05	1.51E−04	7.49E−05	6.81E−05
Chlorobenzene	9.81E−07	4.57E−07	4.63E−07	4.10E−07

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Chloromethane (methyl chloride)	1.74E−08	1.90E−08	−5.10E−09	1.49E−08
Chlorous dissolvent	1.11E−05	7.31E−06	7.49E−06	8.47E−06
Chromium (+III)	1.40E−07	3.34E−07	7.86E−08	1.58E−07
Chromium (+VI)	1.26E−03	1.13E−03	1.46E−03	9.95E−04
Chromium (+VI)	4.39E−04	3.85E−04	4.94E−04	3.39E−04
Chromium (unspecified)	1.15E−05	1.65E−05	1.00E−04	1.44E−05
Chrysene	5.36E−10	1.09E−09	7.00E−10	9.78E−10
Cobalt	4.27E−03	4.11E−03	6.06E−03	3.42E−03
Cobalt	2.95E−05	6.63E−06	2.68E−05	6.44E−06
Copper (+II)	1.42E−02	1.35E−02	1.56E−02	1.13E−02
Copper (+II)	2.49E−05	2.39E−05	7.19E−05	4.95E−05
Cresol (methyl phenol)	4.50E−10	4.65E−10	−3.99E−10	3.44E−10
Cumene (isopropylbenzene)	6.06E−05	3.31E−05	3.95E−05	8.35E−05
Cyanide	2.20E−05	2.53E−05	2.65E−05	1.94E−05
Dichloroethane (ethylene dichloride)	1.47E−06	5.60E−07	1.92E−05	6.48E−07
Dichloromethane (methylene chloride)	1.04E−05	6.90E−06	8.37E−06	6.24E−06
Dichloropropane	3.63E−15	5.58E−15	1.99E−15	4.43E−15
Dichromate	1.25E−06	1.22E−06	1.70E−06	1.03E−06
Dissolved organic carbon, DOC (ecoinvent)	1.40E+00	1.38E+00	2.20E+00	1.14E+00
Ecoinvent long-term to freshwater	2.02E+01	2.06E+01	2.15E+01	1.69E+01
Emissions to freshwater	3.55E+01	3.53E+01	3.90E+01	2.93E+01
Ethanol	2.56E−07	1.19E−07	1.20E−07	1.06E−07
Ethene (ethylene)	6.84E−05	2.64E−05	1.52E−05	4.03E−05
Ethyl benzene	1.47E−05	1.04E−05	1.21E−05	9.23E−06

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Ethylene acetate (ethyl acetate)	1.74E−11	8.10E−12	8.19E−12	7.25E−12
Ethylene oxide	5.11E−08	2.92E−08	2.44E−08	2.83E−08
Ethylenediamine	1.58E−09	1.58E−09	1.59E−09	1.58E−09
Fatty acids (calculated as total carbon)	2.24E−03	1.56E−03	1.83E−03	1.39E−03
Fluoranthene	1.59E−10	3.41E−10	1.95E−10	2.80E−10
Fluoride	4.02E−01	4.13E−01	4.26E−01	3.38E−01
Fluorine	1.36E−07	1.48E−07	1.20E−07	1.25E−07
Formaldehyde (methanal)	7.18E−05	1.95E−05	1.57E−05	2.17E−05
Freshwater	1.94E+01	1.97E+01	2.57E+01	1.61E+01
Halogenated organic emissions to freshwater	2.43E−05	1.56E−05	1.18E−04	1.61E−05
Heavy metals to freshwater	2.37E−02	2.17E−02	3.04E−02	1.83E−02
Heavy metals to water (unspecified)	2.87E−07	3.04E−07	2.51E−07	2.40E−07
Hexafluorosilicates	2.19E−06	1.75E−06	2.13E−06	1.66E−06
Hexane (isomers)	4.94E−11	5.14E−11	−4.33E−11	3.79E−11
Hydrocarbons (unspecified)	8.69E−05	7.86E−05	3.77E−04	1.40E−04
Hydrocarbons to freshwater	4.59E−02	2.92E−02	3.60E−02	2.68E−02
Hydrogen chloride	1.21E−08	1.29E−08	1.24E−08	1.04E−08
Hydrogen fluoride (hydrofluoric acid)	1.23E−09	2.42E−09	−9.55E−09	1.96E−09
Hydrogen peroxide	2.22E−06	1.99E−06	2.08E−06	1.97E−06
Hydrogen sulphide	2.12E−03	2.15E−03	2.76E−03	1.77E−03
Hydrogen sulphide	2.66E−06	2.23E−06	3.36E−06	1.99E−06
Hydroxide	2.36E−04	1.27E−03	1.89E−04	1.88E−04
Hypochlorite	8.90E−06	7.61E−06	1.17E−05	7.73E−06
Inorganic emissions to freshwater	1.09E+01	1.07E+01	1.20E+01	8.93E+00

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Inorganic salts and acids (unspecified)	7.77E−04	1.86E−03	3.13E−02	1.86E−03
Iodide	7.65E−11	5.87E−11	2.88E−10	6.55E−11
Iodide	1.08E−04	9.05E−05	1.01E−04	7.74E−05
Iron	2.64E−01	2.66E−01	3.17E−01	2.21E−01
Iron	1.92E−02	1.77E−02	2.57E−02	1.49E−02
Lead (+II)	2.63E−03	1.81E−03	1.91E−03	1.57E−03
Lead (+II)	2.57E−05	3.13E−05	5.79E−05	2.32E−05
Lithium	1.18E−05	4.65E−05	3.05E−05	9.06E−06
Magnesium (+III)	2.24E+00	2.27E+00	2.38E+00	1.87E+00
Magnesium (+III)	3.90E−02	3.88E−02	4.12E−02	3.21E−02
Magnesium chloride	−3.07E−09	−1.68E−08	−2.46E−09	−2.45E−09
Manganese (+II)	2.33E−02	2.33E−02	2.52E−02	1.93E−02
Manganese (+II)	6.06E−04	6.05E−04	6.33E−04	4.98E−04
Mercury (+II)	4.11E−06	4.01E−06	1.09E−05	3.70E−06
Mercury (+II)	2.19E−06	2.09E−06	2.62E−06	1.74E−06
Metal ions (unspecific)	3.41E−02	2.68E−03	1.02E−02	2.46E−03
Metal ions (unspecific)	0.00E+00	0.00E+00	−3.56E−05	0.00E+00
Metals (unspecified)	1.88E−05	4.18E−05	1.15E−03	4.18E−05
Methanol	6.61E−04	6.35E−04	6.29E−04	5.82E−04
Methyl acrylate	3.78E−07	1.75E−07	1.77E−07	1.57E−07
Methyl amine	8.84E−11	4.12E−11	4.17E−11	3.69E−11
Methyl isobutyl ketone	4.60E−11	1.81E−10	1.19E−10	3.54E−11
Methyl tert-butylether	3.04E−08	1.60E−08	1.01E−08	1.49E−08
Methylformate	2.99E−11	1.39E−11	1.40E−11	1.24E−11

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Molybdenum	3.17E−04	2.98E−04	3.01E−04	2.47E−04
Molybdenum	1.01E−04	8.97E−05	1.00E−04	7.74E−05
Naphthalene	5.99E−08	1.12E−07	7.28E−08	9.66E−08
n-Butyl acetate	1.44E−07	6.71E−08	6.78E−08	6.01E−08
Neutral salts	1.60E−09	1.07E−08	−4.77E−08	6.87E−10
Nickel (+II)	5.30E−03	5.47E−03	1.22E−02	4.62E−03
Nickel (+II)	4.41E−05	4.63E−05	1.04E−04	6.68E−05
Nitrate	1.21E−01	1.24E−01	1.29E−01	1.02E−01
Nitrate	1.66E−01	6.13E−02	6.94E−02	9.12E−02
Nitrite	8.93E−07	6.79E−07	1.52E−04	7.30E−07
Nitrite	1.97E−05	2.02E−05	9.74E−05	1.84E−05
Nitrogen	1.37E−03	1.06E−03	1.59E−03	1.09E−03
Nitrogen organic bounded	2.68E−05	2.03E−05	4.57E−03	2.19E−05
Nitrogen organic bounded	2.05E−04	2.63E−04	3.59E−04	1.81E−04
Oil (unspecified)	4.17E−02	2.62E−02	3.23E−02	2.38E−02
Organic chlorine compounds (unspecified)	2.81E−09	2.81E−09	5.86E−06	2.81E−09
Organic compounds (dissolved)	2.29E−06	2.29E−06	1.26E−04	2.29E−06
Organic compounds (unspecified)	3.31E−09	3.31E−09	1.47E−03	3.31E−09
Organic emissions to freshwater	4.60E−02	2.93E−02	3.78E−02	2.69E−02
Particles to freshwater	1.48E−01	1.68E−01	2.16E−01	1.72E−01
Phenol (hydroxy benzene)	6.40E−05	4.77E−05	5.88E−05	5.23E−05
Phosphate	1.17E−01	1.18E−01	1.25E−01	9.79E−02
Phosphate	7.05E−04	3.82E−04	1.26E−03	3.31E−04
Phosphorus	1.73E−04	8.25E−05	4.12E−04	1.37E−04

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Polychlorinated dibenzo-p-dioxins (2,3,7,8—TCDD)	1.80E−13	1.80E−13	6.17E−08	1.80E−13
Polycyclic aromatic hydrocarbons (PAH, unspec.)	4.84E−06	4.86E−06	3.84E−06	3.46E−06
Potassium	2.48E+00	2.52E+00	2.63E+00	2.08E+00
Potassium	5.19E−01	5.27E−01	5.51E−01	4.35E−01
Propene	2.88E−05	1.70E−05	2.41E−05	6.62E−05
Propylene oxide	3.37E−06	2.70E−06	2.76E−06	2.41E−06
Rubidium	8.55E−06	5.79E−06	6.88E−06	5.19E−06
Scandium	5.89E−06	4.50E−06	8.90E−06	4.41E−06
Scandium	1.40E−06	1.07E−06	2.01E−06	1.05E−06
Selenium	2.87E−04	2.92E−04	3.10E−04	2.41E−04
Selenium	1.42E−04	1.44E−04	1.51E−04	1.19E−04
Silicate particles	−2.87E−09	−6.82E−09	−1.21E−07	−7.04E−09
Silicon dioxide (silica)	9.30E−21	9.30E−21	2.41E−19	9.30E−21
Silver	1.46E−07	1.20E−07	7.49E−07	1.88E−07
Silver	6.25E−07	5.22E−07	5.59E−07	3.99E−07
Sodium (+I)	1.05E+00	1.06E+00	1.13E+00	8.76E−01
Sodium (+I)	6.63E−01	5.79E−01	8.14E−01	4.96E−01
Sodium chloride (rock salt)	3.29E−10	1.75E−09	−5.74E−10	3.39E−10
Sodium formate	1.18E−06	1.17E−06	1.18E−06	1.17E−06
Sodium hypochlorite	7.30E−09	2.43E−08	−4.24E−07	5.77E−09
Soil loss by erosion into water	1.56E−08	4.54E−08	2.09E−08	3.93E−08
Solids (dissolved)	9.07E−02	8.25E−02	2.22E−01	9.13E−02
Solids (suspended)	3.96E+00	3.92E+00	5.63E+00	3.28E+00
Solids (suspended)	1.48E−01	1.68E−01	2.15E−01	1.72E−01

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Strontium	3.98E−04	3.10E−04	1.13E−03	3.09E−04
Strontium	1.91E−03	1.62E−03	1.76E−03	1.38E−03
Sulphate	3.58E+00	3.59E+00	3.80E+00	2.97E+00
Sulphate	1.10E+00	1.12E+00	1.29E+00	9.30E−01
Sulphide	7.68E−05	1.31E−04	9.06E−05	1.14E−04
Sulphite	3.12E−04	3.13E−04	3.43E−04	2.65E−04
Sulphur	2.32E−04	8.72E−05	1.18E−04	7.93E−05
Sulphuric acid	1.56E−06	1.66E−06	1.60E−06	1.34E−06
Suspended solids, unspecified	−1.91E−20	−5.54E−20	−3.19E−20	−1.06E−20
Thallium	2.74E−06	2.65E−06	5.83E−06	2.28E−06
Thallium	9.72E−08	8.37E−08	1.28E−07	8.46E−08
Tin (+IV)	3.56E−03	3.52E−03	6.24E−03	2.91E−03
Tin (+IV)	1.14E−06	1.13E−06	1.68E−06	1.09E−06
Titanium	5.92E−05	6.31E−06	1.01E−05	5.80E−06
Toluene (methyl benzene)	7.16E−05	5.16E−05	6.11E−05	4.57E−05
Total dissolved organic bounded carbon	1.41E−01	3.07E−02	3.73E−02	2.80E−02
Total organic bounded carbon	1.44E−01	3.37E−02	4.14E−02	3.83E−02
Trichloromethane (chloroform)	2.26E−09	1.05E−09	1.06E−09	9.41E−10
Tungsten	3.26E−06	2.50E−06	4.43E−06	2.47E−06
Tungsten	1.98E−06	1.52E−06	2.67E−06	1.50E−06
Vanadium (+III)	1.07E−03	9.44E−04	1.66E−03	7.94E−04
Vanadium (+III)	8.97E−06	8.31E−06	1.11E−05	7.14E−06
Vinyl chloride (VCM; chloroethene)	1.71E−07	1.10E−07	7.84E−05	1.13E−07
VOC (unspecified)	2.17E−04	1.51E−04	1.79E−04	1.35E−04

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Xylene (isomers; dimethyl benzene)	5.89E−05	4.21E−05	4.80E−05	3.73E−05
Xylene (meta-Xylene; 1,3-Dimethylbenzene)	3.32E−10	1.31E−09	8.61E−10	2.55E−10
Xylene (ortho-xylene; 1,2-Dimethylbenzene)	2.42E−10	9.54E−10	6.27E−10	1.86E−10
Zinc (+II)	3.46E−02	1.27E−02	4.05E−03	1.23E−02
Zinc (+II)	1.78E−04	1.43E−04	2.18E−04	1.21E−04
Emissions to agricultural soil				
2,4-dichlorophenoxyacetic acid (2,4-D)	2.37E−08	2.13E−08	2.21E−08	2.08E−08
Aclonifen	1.38E−05	1.49E−07	8.68E−08	1.37E−07
Aldrin	4.38E−10	2.04E−10	2.05E−10	1.82E−10
Aluminium	6.80E−03	6.79E−03	7.08E−03	5.60E−03
Antimony	1.65E−07	1.65E−07	1.65E−07	1.65E−07
Arsenic (+V)	2.26E−06	2.26E−06	2.34E−06	1.87E−06
Atrazine	1.15E−10	5.34E−11	5.39E−11	4.78E−11
Barium	3.16E−06	3.16E−06	3.16E−06	3.16E−06
Benomyl	1.51E−10	1.36E−10	1.41E−10	1.33E−10
Bentazone	7.05E−06	7.60E−08	4.43E−08	6.98E−08
Cadmium (+II)	5.35E−06	4.66E−06	4.83E−06	3.85E−06
Carbetamide	2.50E−06	3.17E−08	2.06E−08	2.95E−08
Carbofuran	8.26E−08	7.44E−08	7.72E−08	7.28E−08
Carbon (unspecified)	4.22E−03	4.20E−03	4.91E−03	3.48E−03
Chlorine	1.04E−03	1.04E−03	1.08E−03	8.58E−04
Chlorothalonil	4.78E−06	4.78E−06	4.81E−06	4.76E−06
Chromium (unspecified)	6.94E−05	6.39E−05	6.63E−05	5.27E−05
Cobalt	5.87E−06	5.87E−06	6.10E−06	4.84E−06

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Copper (+II)	4.97E−05	5.40E−05	5.68E−05	4.46E−05
Cypermethrin	6.62E−08	1.13E−08	1.15E−08	1.11E−08
Different pollutants	1.48E−01	1.48E−01	1.53E−01	1.22E−01
Emissions to agricultural soil	2.36E−01	2.14E−01	2.29E−01	1.80E−01
Fenpiclonil	6.65E−07	1.93E−07	1.92E−07	1.92E−07
Glyphosate	7.05E−07	6.56E−07	6.75E−07	5.88E−07
Heavy metals to agricultural soil	1.54E−02	1.53E−02	1.63E−02	1.26E−02
Inorganic emissions to agricultural soil	1.41E−02	1.40E−02	1.46E−02	1.16E−02
Iron	7.65E−03	7.63E−03	8.33E−03	6.30E−03
Lead (+II)	2.29E−05	2.18E−05	2.28E−05	1.81E−05
Linuron	1.06E−04	1.15E−06	6.69E−07	1.05E−06
Mancozeb	6.20E−06	6.20E−06	6.24E−06	6.18E−06
Manganese (+II)	6.51E−03	6.51E−03	6.74E−03	5.36E−03
Mercury (+II)	1.27E−07	3.69E−08	4.22E−08	3.08E−08
Metaldehyde	4.72E−07	7.20E−09	5.10E−09	6.78E−09
Metolachlor	7.71E−04	8.30E−06	4.84E−06	7.63E−06
Metribuzin	2.18E−07	2.18E−07	2.20E−07	2.18E−07
Molybdenum	1.21E−06	1.21E−06	1.27E−06	9.99E−07
Napropamide	8.36E−07	1.27E−08	9.03E−09	1.20E−08
Nickel (+II)	1.74E−05	1.83E−05	1.90E−05	1.51E−05
Oil (unspecified)	5.35E−02	3.31E−02	3.96E−02	3.01E−02
Orbencarb	1.18E−06	1.18E−06	1.19E−06	1.18E−06
Organic emissions to agricultural soil	5.77E−02	3.73E−02	4.45E−02	3.36E−02
Other emissions to agricultural soil	1.49E−01	1.48E−01	1.53E−01	1.22E−01

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Pesticides to agricultural soil	9.18E−04	2.31E−05	1.91E−05	2.22E−05
Phosphorus	3.19E−03	3.19E−03	3.30E−03	2.63E−03
Pirimicarb	6.67E−07	7.19E−09	4.19E−09	6.61E−09
Strontium	2.72E−08	2.38E−08	2.73E−08	2.12E−08
Sulphur	3.02E−03	3.02E−03	3.18E−03	2.49E−03
Sulphuric acid	2.21E−11	1.03E−11	1.03E−11	9.19E−12
Tebutam	1.98E−06	3.02E−08	2.14E−08	2.84E−08
Teflubenzuron	1.46E−08	1.46E−08	1.47E−08	1.45E−08
Thiram	2.67E−10	2.41E−10	2.50E−10	2.36E−10
Tin (+IV)	3.57E−07	3.55E−07	4.20E−07	3.51E−07
Titanium	4.49E−04	4.49E−04	4.65E−04	3.70E−04
Vanadium (+III)	1.29E−05	1.29E−05	1.33E−05	1.06E−05
Zinc (+II)	5.59E−04	5.43E−04	5.65E−04	4.48E−04
Emissions to industrial soil				
Aluminium	4.12E−04	2.72E−04	3.31E−04	2.46E−04
Aluminium (+III)	7.37E−07	1.52E−06	9.21E−07	1.28E−06
Ammonia	3.45E−04	6.98E−04	4.33E−04	5.95E−04
Arsenic (+V)	1.65E−07	1.10E−07	1.33E−07	9.90E−08
Barium	2.06E−04	1.36E−04	1.65E−04	1.23E−04
Bromide	9.86E−08	2.03E−07	1.25E−07	1.73E−07
Cadmium (+II)	1.41E−08	1.24E−08	−6.97E−08	1.02E−08
Calcium (+II)	1.66E−03	1.10E−03	1.33E−03	9.91E−04
Carbon (unspecified)	1.24E−03	8.17E−04	9.92E−04	7.39E−04
Chloride	1.15E−04	2.37E−04	1.46E−04	2.02E−04

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Chlorine	2.45E−02	2.31E−02	3.62E−02	2.03E−02
Chromium (+III)	1.12E−10	1.21E−10	1.17E−10	9.63E−11
Chromium (+VI)	1.01E−05	8.42E−06	2.51E−05	7.67E−06
Chromium (unspecified)	2.78E−06	2.76E−06	2.53E−06	2.42E−06
Cobalt	1.15E−08	2.37E−08	1.45E−08	2.02E−08
Copper (+II)	7.43E−06	6.20E−06	1.66E−05	5.72E−06
Different pollutants	4.72E−05	3.15E−05	4.08E−05	2.85E−05
Emissions to industrial soil	1.90E−01	1.90E−01	2.18E−01	1.57E−01
Fluoride	1.53E−01	1.56E−01	1.61E−01	1.27E−01
Glyphosate	2.36E−06	2.00E−06	2.08E−06	1.92E−06
Heavy metals to industrial soil	5.69E−03	4.93E−03	6.12E−03	4.65E−03
Inorganic emissions to industrial soil	1.83E−01	1.84E−01	2.10E−01	1.52E−01
Iron	5.38E−03	4.42E−03	5.74E−03	4.21E−03
Lead (+II)	5.66E−07	5.11E−07	5.24E−07	4.55E−07
Magnesium (+III)	3.31E−04	2.19E−04	2.65E−04	1.98E−04
Manganese (+II)	1.66E−05	1.12E−05	1.34E−05	1.01E−05
Mercury (+II)	1.39E−11	2.78E−11	1.74E−11	2.36E−11
Nickel (+II)	4.07E−07	6.12E−07	4.28E−07	5.06E−07
Oil (unspecified)	3.21E−04	2.24E−04	2.26E−04	1.98E−04
Organic emissions to industrial soil	1.56E−03	1.04E−03	1.22E−03	9.37E−04
Other emissions to industrial soil	4.95E−05	3.35E−05	4.29E−05	3.04E−05
Pesticides to industrial soil	2.36E−06	2.00E−06	2.08E−06	1.92E−06
Phosphorus	5.64E−05	8.56E−05	6.13E−05	7.37E−05
Potassium (+I)	2.28E−04	2.67E−04	2.20E−04	2.32E−04

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Sodium (+I)	1.11E−03	1.13E−03	9.47E−03	1.07E−03
Strontium	2.24E−04	4.45E−04	2.78E−04	3.80E−04
Sulphate	1.09E−05	2.22E−05	1.36E−05	1.88E−05
Sulphide	6.56E−05	1.33E−04	8.17E−05	1.13E−04
Sulphur	2.47E−04	1.63E−04	1.98E−04	1.48E−04
Zinc (+II)	4.51E−05	3.93E−05	4.10E−05	3.50E−05
Emissions to seawater				
Acenaphthene	5.53E−07	5.96E−07	5.97E−07	4.97E−07
Acenaphthylene	2.10E−07	2.26E−07	2.26E−07	1.88E−07
Acetic acid	1.04E−07	1.96E−07	1.41E−07	1.82E−07
Adsorbable organic halogen compounds (AOX)	9.38E−08	5.75E−08	6.98E−08	5.22E−08
Alkane (unspecified)	3.14E−05	1.96E−05	2.38E−05	1.78E−05
Alkene (unspecified)	2.90E−06	1.81E−06	2.20E−06	1.65E−06
Aluminium (+III)	8.43E−05	6.02E−05	7.50E−05	5.52E−05
Ammonia	4.59E−08	4.73E−08	−4.07E−08	3.51E−08
Ammonium/ammonia	2.93E−05	1.77E−05	2.15E−05	1.60E−05
Analytical measures to sea water	2.64E+00	2.58E+00	3.67E+00	2.13E+00
Anthracene	1.22E−07	1.33E−07	1.32E−07	1.10E−07
Aromatic hydrocarbons (unspecified)	1.36E−04	8.51E−05	1.03E−04	7.73E−05
Arsenic (+V)	1.42E−06	1.45E−06	1.10E−06	1.17E−06
Barium	4.15E−04	3.63E−04	3.83E−04	3.13E−04
Barytes	4.18E−03	2.83E−03	3.55E−03	2.59E−03
Benzene	1.18E−04	1.17E−04	1.20E−04	9.79E−05
Benzo(a)anthracene	1.25E−07	1.35E−07	1.35E−07	1.13E−07

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Benzofluoranthene	1.41E−07	1.52E−07	1.52E−07	1.26E−07
Beryllium	3.39E−07	3.79E−07	3.70E−07	3.18E−07
Biological oxygen demand (BOD)	1.19E+00	1.16E+00	1.43E+00	9.59E−01
Boron	2.06E−06	1.27E−06	1.48E−06	1.15E−06
Bromine	1.69E−04	1.06E−04	1.28E−04	9.60E−05
Cadmium (+II)	1.51E−06	1.60E−06	1.39E−06	1.28E−06
Calcium (+II)	1.55E−02	7.29E−03	8.32E−03	6.79E−03
Carbonate	1.25E−02	1.42E−02	1.36E−02	1.19E−02
Cesium	2.42E−07	1.51E−07	1.83E−07	1.37E−07
Chemical oxygen demand (COD)	2.89E−02	2.01E−02	2.43E−02	1.80E−02
Chloride	1.10E+00	1.19E+00	1.16E+00	9.99E−01
Chlorous dissolvent	3.82E−13	1.86E−13	1.10E−13	1.71E−13
Chromium (unspecified)	1.28E−06	2.37E−06	1.31E−06	1.59E−06
Chrysene	7.11E−07	7.66E−07	7.67E−07	6.39E−07
Cobalt	5.94E−06	6.63E−06	6.48E−06	5.56E−06
Copper (+II)	4.29E−06	4.29E−06	3.74E−06	3.50E−06
Cresol (methyl phenol)	3.46E−10	3.56E−10	−3.07E−10	2.65E−10
Cyanide	2.77E−06	1.41E−06	1.53E−06	1.27E−06
Emissions to sea water	4.03E+00	3.90E+00	4.98E+00	3.25E+00
Ethyl benzene	3.36E−05	3.26E−05	3.41E−05	2.72E−05
Fatty acids (calculated as total carbon)	1.38E−03	8.65E−04	1.05E−03	7.87E−04
Fluoranthene	1.46E−07	1.58E−07	1.58E−07	1.31E−07
Fluoride	1.08E−04	4.22E−05	4.58E−05	4.00E−05
Glutaraldehyde	5.16E−07	3.50E−07	4.38E−07	3.20E−07
Halogenated organic emissions to sea water	3.82E−13	1.86E−13	1.10E−13	1.71E−13

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Heavy metals to sea water	9.17E−04	6.89E−04	7.79E−04	6.09E−04
Hexane (isomers)	3.78E−11	3.89E−11	−3.35E−11	2.89E−11
Hydrocarbons (unspecified)	7.85E−05	5.30E−05	6.65E−05	4.86E−05
Hydrocarbons to sea water	1.15E−02	8.14E−03	9.72E−03	7.26E−03
Hypochlorite	9.27E−06	7.93E−06	1.22E−05	8.06E−06
Inorganic emissions to sea water	1.35E+00	1.28E+00	1.26E+00	1.08E+00
Iodide	2.42E−05	1.51E−05	1.83E−05	1.37E−05
Iron	9.41E−05	8.97E−05	8.95E−05	7.58E−05
Lead (+II)	2.58E−06	1.96E−06	2.11E−06	1.71E−06
Magnesium	1.34E−03	8.38E−04	1.01E−03	7.61E−04
Manganese (+II)	1.86E−05	1.53E−05	1.65E−05	1.33E−05
Mercury (+II)	5.02E−08	5.30E−08	5.24E−08	4.45E−08
Methanol	6.30E−06	4.46E−06	5.89E−06	3.99E−06
Methyl tert-butylether	1.62E−06	9.82E−07	1.19E−06	8.92E−07
Molybdenum	5.11E−08	3.11E−08	3.75E−08	2.83E−08
Naphthalene	1.61E−05	1.75E−05	1.74E−05	1.46E−05
Nickel (+II)	3.68E−06	3.92E−06	3.65E−06	3.26E−06
Nitrate	1.33E−04	1.02E−04	1.41E−04	9.56E−05
Nitrite	1.56E−06	1.19E−06	1.91E−06	1.18E−06
Nitrogen	1.17E−06	7.45E−07	9.09E−07	6.75E−07
Nitrogen organic bounded	5.62E−05	2.75E−05	3.35E−05	2.55E−05
Oil (unspecified)	9.32E−03	6.58E−03	7.91E−03	5.87E−03
Organic emissions to sea water	1.15E−02	8.16E−03	9.74E−03	7.27E−03
Other emissions to sea water	1.78E−06	9.29E−07	1.29E−06	8.62E−07
Particles to sea water	3.82E−02	3.54E−02	3.72E−02	2.99E−02

(continued)

Table 39.34 (continued)

Substance	W	W/ALU	PVC	W/C
Pesticides to sea water	1.78E−06	9.29E−07	1.29E−06	8.62E−07
Phenol (hydroxy benzene)	1.74E−04	1.77E−04	1.79E−04	1.49E−04
Phosphate	3.52E−04	1.14E−04	1.16E−04	1.11E−04
Phosphorus	2.00E−06	1.22E−06	1.49E−06	1.11E−06
Polycyclic aromatic hydrocarbons (PAH, unspec.)	1.92E−06	1.20E−06	1.46E−06	1.09E−06
Potassium	1.02E−03	6.38E−04	7.74E−04	5.80E−04
Selenium	7.64E−08	4.64E−08	5.63E−08	4.22E−08
Silver	1.45E−07	9.10E−08	1.10E−07	8.26E−08
Sodium (+I)	7.46E−02	4.69E−02	5.67E−02	4.25E−02
Solids (suspended)	3.82E−02	3.54E−02	3.72E−02	2.99E−02
Strontium	4.40E−04	2.75E−04	3.33E−04	2.50E−04
Sulphate	1.35E−01	1.47E−02	1.48E−02	1.33E−02
Sulphide	2.01E−03	2.31E−03	2.20E−03	1.94E−03
Sulphur	3.78E−06	2.40E−06	2.89E−06	2.17E−06
Tin (+IV)	4.71E−10	4.85E−10	−4.18E−10	3.60E−10
Titanium	2.08E−08	1.50E−08	1.85E−08	1.37E−08
Toluene (methyl benzene)	1.14E−04	1.05E−04	1.10E−04	8.81E−05
Total dissolved organic bounded carbon	8.89E−03	5.95E−03	7.29E−03	5.36E−03
Total organic bounded carbon	1.41E+00	1.39E+00	2.21E+00	1.15E+00
Tributyltinoxide	1.78E−06	9.29E−07	1.29E−06	8.62E−07
Triethylene glycol	5.35E−06	3.82E−06	5.04E−06	3.43E−06
Vanadium (+III)	4.22E−06	4.64E−06	4.55E−06	3.90E−06
VOC (unspecified)	8.45E−05	5.28E−05	6.41E−05	4.80E−05
Xylene (isomers; dimethyl benzene)	4.32E−05	3.56E−05	3.80E−05	3.12E−05
Zinc (+II)	3.40E−04	2.81E−04	3.15E−04	2.47E−04

Table 39.35 Normalised sensitivity coefficients computed for 10% perturbance of amount of wood in the frame

Impact category	Normalised sensitivity coefficient			
	W	W/ALU	PVC	W/C
Land use	*8.8E−01*	*7.5E−01*	0.0E+00	*7.3E−01*
Climate change	5.4E−02	1.7E−02	0.0E+00	1.9E−02
Freshwater ecotoxicity	6.3E−02	2.0E−02	0.0E+00	2.3E−02
Freshwater eutrophication	−7.3E−03	−2.2E−03	0.0E+00	−2.7E−03
Human toxicity (cancer)	2.0E−03	6.2E−04	0.0E+00	7.5E−04
Ionising radiation (human health)	7.8E−02	2.3E−02	0.0E+00	2.6E−02
Human toxicity (non-cancer)	6.1E−02	1.9E−02	0.0E+00	2.3E−02
Marine eutrophication	9.1E−03	2.9E−03	0.0E+00	3.2E−03
Resource depletion (minerals, fossils)	3.2E−02	9.8E−03	0.0E+00	8.5E−03
Stratospheric ozone depletion	2.4E−02	7.6E−03	0.0E+00	6.5E−03
Particulate matter formation	2.1E−02	6.3E−03	0.0E+00	7.0E−03
Photochemical ozone formation	1.2E−02	3.7E−03	0.0E+00	4.3E−03
Terrestrial acidification	1.7E−02	5.0E−03	0.0E+00	5.6E−03

Values >0.3 are in italics

Table 39.36 Normalised sensitivity coefficients computed for 10% perturbance of amount of steel in the frame

Impact category	Normalised sensitivity coefficient			
	W	W/ALU	PVC	W/C
Land use	1.3E−04	9.0E−04	6.3E−02	8.8E−04
Climate change	1.0E−03	2.6E−03	4.3E−02	2.8E−03
Freshwater ecotoxicity	5.1E−03	1.3E−02	1.9E−01	1.5E−02
Freshwater eutrophication	1.8E−04	4.4E−04	7.9E−03	5.3E−04
Human toxicity (cancer)	2.4E−04	5.6E−04	1.0E−02	6.8E−04
Ionising radiation (human health)	6.7E−03	1.6E−02	2.8E−01	1.8E−02
Human toxicity (non-cancer)	6.0E−03	1.5E−02	2.2E−01	1.7E−02
Marine eutrophication	5.1E−04	1.2E−03	2.3E−02	1.4E−03
Resource depletion (minerals, fossils)	3.5E−02	8.4E−02	*6.4E−01*	7.3E−02
Stratospheric ozone depletion	2.7E−03	6.6E−03	1.2E−01	5.7E−03
Particulate matter formation	2.3E−03	5.4E−03	9.6E−02	6.0E−03
Photochemical ozone formation	5.6E−04	1.3E−03	2.4E−02	1.5E−03
Terrestrial acidification	1.4E−03	3.5E−03	7.0E−02	3.8E−03

Values >0.3 are in italics

Table 39.37 Normalised sensitivity coefficients computed for 10% perturbance of amount of glass in the pane

Impact category	Normalised sensitivity coefficient			
	W	W/ALU	PVC	W/C
Land use	6.2E−03	1.7E−02	6.3E−02	2.5E−02
Climate change	2.3E−02	2.3E−02	2.1E−02	3.8E−02
Freshwater ecotoxicity	8.8E−03	9.1E−03	7.3E−03	1.6E−02
Freshwater eutrophication	1.6E−03	1.6E−03	1.5E−03	2.9E−03
Human toxicity (cancer)	2.6E−03	2.5E−03	2.4E−03	4.6E−03
Ionising radiation (human health)	1.1E−01	1.1E−01	9.8E−02	1.8E−01
Human toxicity (non-cancer)	9.1E−03	9.4E−03	7.3E−03	1.7E−02
Marine eutrophication	2.8E−02	2.9E−02	2.7E−02	4.8E−02
Resource depletion (minerals, fossils)	*4.5E−01*	*4.5E−01*	1.8E−01	*5.9E−01*
Stratospheric ozone depletion	6.2E−02	6.4E−02	6.2E−02	8.3E−02
Particulate matter formation	5.4E−02	5.4E−02	4.6E−02	9.0E−02
Photochemical ozone formation	3.4E−02	3.4E−02	3.1E−02	5.8E−02
Terrestrial acidification	5.7E−02	5.7E−02	4.8E−02	9.5E−02

Values >0.3 are in italics

Table 39.38 Normalised sensitivity coefficients computed for 10% perturbance of *U*-values

Impact category	Normalised sensitivity coefficient			
	W	W/ALU	PVC	W/C
Land use	*8.2E−01*	*8.6E−01*	*7.9E−01*	*7.7E−01*
Climate change	*9.0E−01*	*9.5E−01*	*7.9E−01*	*9.2E−01*
Freshwater ecotoxicity	*1.0E+00*	*1.0E+00*	*9.9E−01*	*1.0E+00*
Freshwater eutrophication	*9.9E−01*	*9.9E−01*	*9.9E−01*	*9.9E−01*
Human toxicity (cancer)	*5.7E−01*	*5.7E−01*	*5.4E−01*	*5.2E−01*
Ionising radiation (human health)	*9.0E−01*	*9.5E−01*	*7.7E−01*	*9.2E−01*
Human toxicity (non-cancer)	*9.0E−01*	*9.4E−01*	*9.0E−01*	*8.7E−01*
Marine eutrophication	*3.8E−01*	*3.9E−01*	1.6E−01	2.8E−01
Resource depletion (minerals, fossils)	*5.5E−01*	*5.7E−01*	*5.8E−01*	*4.1E−01*
Stratospheric ozone depletion	*8.3E−01*	*8.5E−01*	*7.5E−01*	*7.7E−01*
Particulate matter formation	*9.1E−01*	*9.2E−01*	*8.8E−01*	*8.7E−01*
Photochemical ozone formation	*8.2E−01*	*8.3E−01*	*7.3E−01*	*7.6E−01*
Terrestrial acidification	*8.2E−01*	*8.6E−01*	*7.9E−01*	*7.7E−01*

Values >0.3 are in italics

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Disclaimer

This report is based on an LCA that was delivered as part of the requirements to pass the MSc course "Life Cycle Assessment of Products and Systems", given at the Department of Management Engineering of the Technical University of Denmark. The report has been reworked somewhat to serve as an example report to illustrate to students how to perform and how to structure the report on an LCA according to the requirements of ISO 14044:2006 (ISO 2006) and the reporting template in Chap. 38 from the ILCD Handbook (EC-JRC 2010). The reader should note that it is not the intention to provide an example of “the perfect LCA study” or “the perfect LCA report”. The results of this LCA should not be directly used to inform a choice between windows, not even in Denmark. As a result of students collaborating in project teams of 5–6 members during one semester (~ 13 weeks, 10 ECTS MSc course), this is primarily the result of a well-achieved learning experience from LCA beginners. Its main purpose is to illustrate reporting, not good or best LCA practice, which is why many details are not necessarily handled the way they should be according to part II of the book, because there are many constraints on what can be achieved in one semester of learning LCA. LCA studies and reports produced by experienced LCA professionals can have a wide range of different structures and follow different emphases depending on the goal of the study.

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