9 Applying LCA – Comparing two Windows

9.1 Prerequisites

9.1.1 The Objective of the Study

In this chapter Life Cycle Assessments and a comparison of environmental profiles of two products (comparative LCA) will be made to illustrate all steps necessary to perform a full-scale LCA in practice using the previously described methodology.

The aim of the analysis is to check which of the two products, a PVC or an aluminium framed window, is more advisable from an environmental point of view. Moreover, we should also determine which life stages and processes constitute the majority of the environmental burden associated with the two products.

The main objective of the study is educational. The results of the analysis should thus not be used externally, e.g. for commercials or marketing claims. However, the results could be interesting for producers of windows who want to diminish the environmental consequences of their activity, as well as clients of building firms, or non-governmental organisations intending to influence the public, etc.

The analysis has been conducted using SimaPro 5.0 software with the application of the SimaPro Eco-indicator 99 database and different indicators, available in SimaPro methods library as one of the most universal applications. It should be stressed, however, that relying on one single database is a significant limitation of the analysis.

When summarising the results of the LCA, it should be emphasised that performing an LCA is a complex task. In its initial phase it requires a careful life cycle inventory and the collection and correction of data. Good data quality is a precondition for a reliable outcome. The necessity of introducing simplifying assumptions and the lack of standard methodology, especially for the normalisation and weighting phases, make the final result of the LCAs described here unsuitable for commercial applications.

In this Chapter

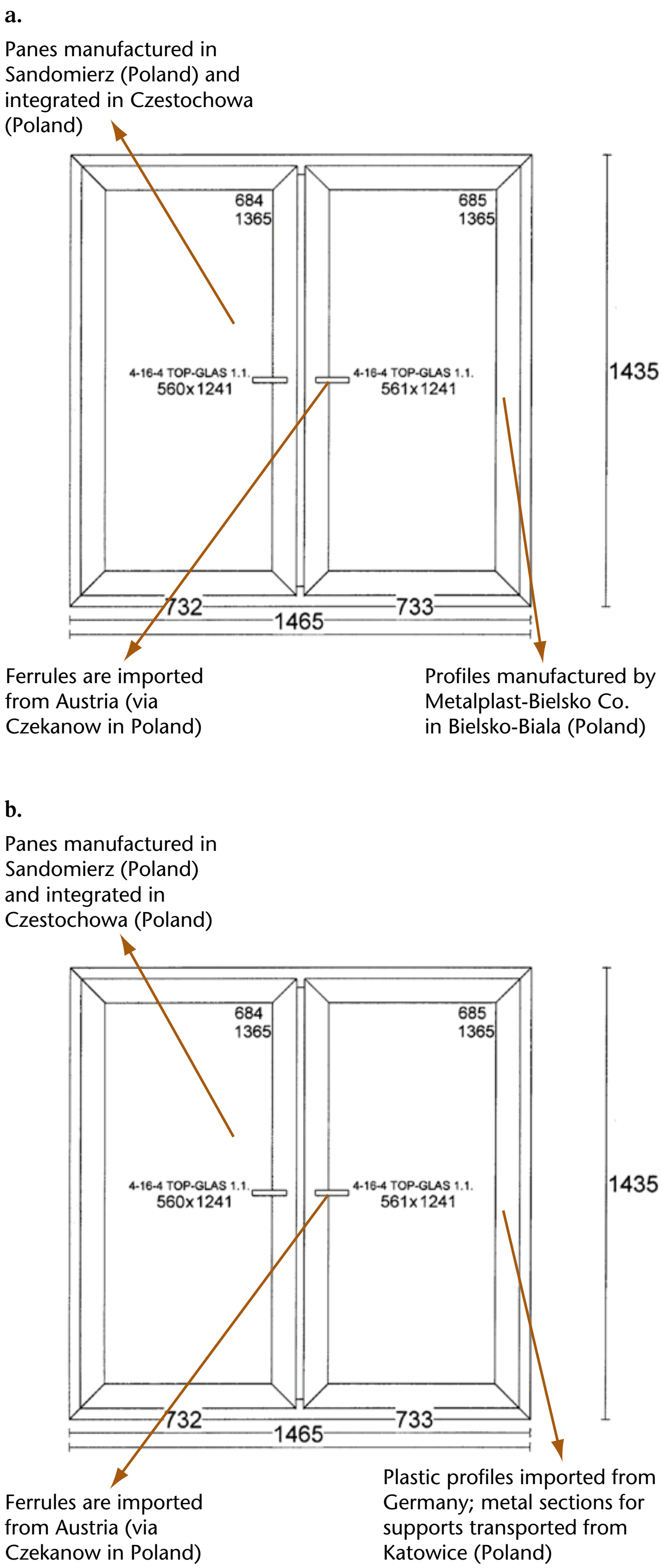


Figure 9.1 Basic data for the two windows. a. *The aluminium frame window.* **b.** *The PVC (polyvinyl chloride) frame window.*

9.1.2 The Windows

The aluminium frame window, the *Alu window*, with basic technical information is shown in Figure 9.1a, and the plastic frame *PVC window* (PVC = polyvinyl chloride) with basic technical information in Figure 9.1b. We will first go through the entire analysis for the aluminium window and then do the same with the PVC window. We will end with a discussion of how the results from the two analyses can be compared, and draw conclusions.

To start the LCA analysis, a *functional unit* must be defined. The functional unit has been defined as a symmetrical window with two sashes which can be installed in the outside wall of a building (this means that an aluminium window has to have a thermal barrier); dimensions: 1465x1435 mm. Lengths of life have been estimated to be 40 years for the plastic window and 50 years for the aluminium window. As a result of the different length of life, in the LCA analysis 1.0 aluminium window will be compared with 1.25 PVC windows, (50/40 = 1.25).

The windows are both considered to be produced and used in the area of Lodz in central Poland. This is important for the calculation of the environmental impact from the transport of materials to the windows.

9.2 The Aluminium "ALU" Window LCA

9.2.1 Life Cycle Inventory

The first step of LCA is to perform a Life Cycle Inventory. Figure 9.2 shows all inflows and outflows for all life cycle phases which were taken into account in the analysis. All the technical data were derived from one of the companies installing windows in Lodz, Poland. Basic technical data collected for the LCA analysis of the aluminium window are given in Table 9.1.

The total mass of an aluminium window is 63.55 kg. Of this, 25.4 kg is the weight of the aluminium profiles (24.9 kg) and handles (0.5 kg). The aluminium profiles are produced by Metalplast-Bielsko Co., Poland, in an extrusion process. (Extrusion means that something is formed by forcing or pushing it out, especially through a small opening, i.a. used for aluminium materials, e.g. extruded aluminium rods.) The transport distance from Bielsko to Lodz is 254 km.

Ferrules and anchors, comprising 2.75 kg of high quality steel, were imported from Austria via Czekanów (transport distance 600 km).

The *float* type glass used, a total of 30.4 kg, was produced in Sandomierz (Poland). It is integrated hermetically into window panes in Czestochowa (transport distance 320 km).

Other materials, a total of 5.5 kg, are plastic, including the polyamide thermal barriers and the gaskets of ethylene-propylene rubber (EPDM).

During 50-year use, the window is assumed to require two replacements of ferrules (about every 20 years) and four replacements of gaskets (every 10 years). These elements have their own life cycles. The replaced ferrules are scrapped and gaskets are discarded. We assume that the window is dismounted after 50 years. Aluminium elements, handles, ferrules, anchors and window panes can be recycled. The rest, i.e. gaskets and the thermal barrier, are discarded, partly incinerated and partly land filled (according to a Dutch scenario of municipal waste utilisation). Instead of dividing the transport according to particular groups of objects, it is assumed that the whole window is transported a distance of 50 km.

Due to the lack of sufficient data, the following operations have been neglected in the analysis:

- Window cleaning.
- Powder coating of the aluminium profiles with the chromated polyester lacquer.
- Joining the elements with glue.
- Filling the cracks between the window and the wall with polyurethane foam and glass fibre and sealing them with silicone.
- Elements necessary for glass integration (small amounts of butyl, thioplast and aluminium frames).

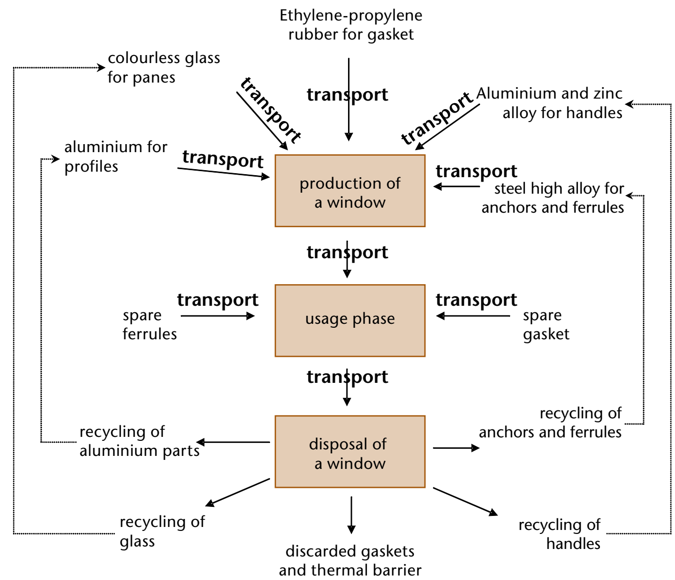


Figure 9.2 Inventory of inflows and outflows. *The inventory diagram for the life cycle of the aluminium frame window.*

Table 9.1 Technical data for LCA of the aluminium window. *Data for aluminium profile made of aluminium alloy $AlMgSiO_5$ with a thermal barrier made of polyamide strengthened with glass fibre (PA 6.6). The thermal barrier is estimated to be 10% of the mass of the profile with the thermal barrier consisting of frame, muntin and sashes. The weight of the gasket is estimated to be 0.015 kg/running meter. The glass is estimated to be 1 mm thick and have a total weight of 2.5 kg/m². The weight of the ferrule is estimated to be 2.5 kg and the anchors 0.25 kg.*

Aluminium profiles			
Element	Length (m)	Mass/metre (kg)	Mass (kg)
Frame	5.8	1.6	9.28
Muntin	1.367	0.79	1.08
Sashes	8.29	1.75	14.51
Other elements (estimated)			2
Thermal barrier			2.5
Total			29.37

Other elements and accessories			
Name	Material	Quantity	Mass (kg)
Gasket	Ethylene-propylene rubber (EPDM)	~ 32 m	0.5
Panes	Colourless glass	Two double integrated panes 4/16/4 of size 594x1279.	30.4
Ferrules and anchors	High-quality steel	1 set	2.75
Handles	Aluminium and zinc alloy (ZnAl)	1 set	0.5
Total			34.15

9.2.2 Process Trees

The next step in the LCA is to generate a *process tree* (Figure 9.3) on the basis of the inventory analysis and all available technical information (Table 9.1). Figure 9.3a illustrates a full process tree of an aluminium window produced by SimaPro. The grey boxes in the figure schematically represent subsequent technological processes grouped into life phases (production, usage, disposal).

The database used to elaborate the life cycle of the aluminium window and the process tree is part of the SimaPro software. The inventory table consists of 595 items, which illustrates the huge number of inflows and outflows connected with an aluminium window life cycle. Selected items of this inventory table are shown in Table 9.2. Accessing, collecting, and interpreting this amount of data is one of the biggest challenges encountered in an LCA process. The figure shows how complex a process tree can be even for such a simple object as a window.

To make a picture of an LCA process more transparent, certain processes, inflows and outflows can be grouped and represented by only one box. Such a *simplified process tree* can be generated by SimaPro (and most other LCA software packages). The simplified process tree for an aluminium window (Figure 9.3b) includes environmental indices of the life cycle phases calculated according to Eco-indicator 99 method. The thickness of lines graphically illustrates the level of environmental impact of the particular processes constituting the life cycle of the window. Brown lines with arrows in the reverse direction reflect the waste utilisation process, energy recovery, and recycling, etc., in the product life cycle. Negative values in the boxes result from the fact that emissions avoided due to recycling or energy recovery have been subtracted from the total environmental impact.

In Figure 9.4 a single element, a *process box*, of the process tree is described. Each process box contains the following information:

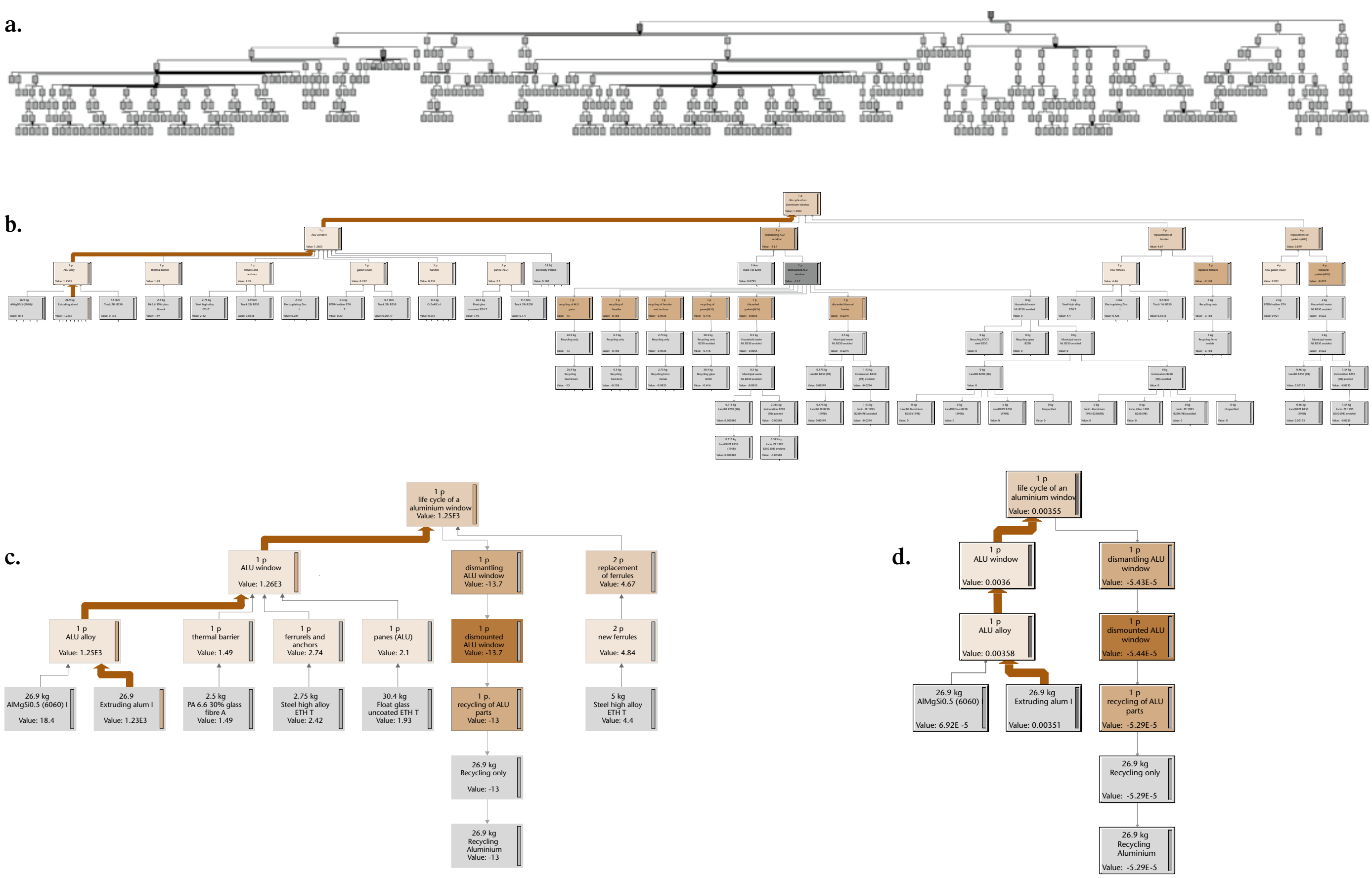


Figure 9.3 Process trees for and LCA of the aluminium frame window. a. *Full process tree for a life cycle of the aluminium frame window generated by SimaPro.* **b.** *Simplified process tree in which several processes are grouped into one box. This includes environmental indices calculated according to Eco-indicator 99. The thickness of the lines is proportional to the environmental impact.* **c.** *Simplified process tree in which only elements with an environmental index larger that 0.1% are included.* **d.** *Simplified process tree in which only elements with an environmental index larger that 1% for the impact category climate change are included.*

- The value of the calculated quantity (partial environmental index, selected emissions, normalised or weighted damage indicators, etc.).
- The quantity (in pieces, kilograms, litres, etc.).
- The name of the material.
- The process of life stage (e.g. aluminium alloy, truck, high steel alloy, etc.).
- The environmental "thermometer".

The process box shows how to calculate two important parameters, the environmental index and the environmental "thermometer". The index shows the impact of the element in the tree. The "thermometer" indicates the relative contribution of the calculated quantity to a single score, to an impact category or a single emission. E.g. when you select CO_2 emissions, the thermometer will display the relative contribution of the process to the CO_2 emissions in the whole life cycle.

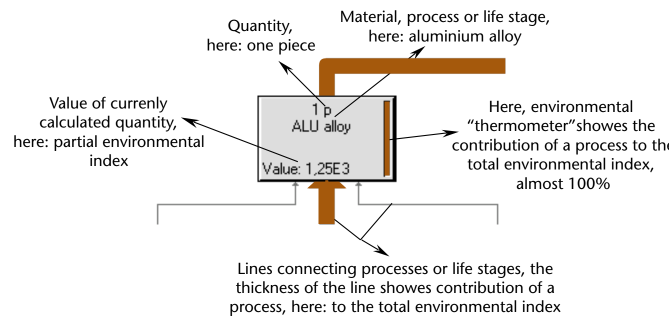


Figure 9.4 A process box for the calculation of an environmental index. *The calculation is made for an item in the life cycle of the aluminium frame window. The process box contains the life stage, the material, the quantity, the environmental index for that impact, and the thermometer showing the contribution of the process to the total environmental index.*

Table 9.2 Inventory table for the life cycle of the aluminium frame window. *The table is generated by the SimaPro software and its database and contains 595 entries.*

No	Substance	Comp/	Unit	Total	ALU window	dismantling ALU wi	replacement of lea	replacement of gas
1	acids	Raw	kg	0	x	0	x	x
2	additions	Raw	g	-47,5	x	-47,5	x	x
3	additives	Raw	kg	0	x	0	x	x
4	air	Raw	oz	109	117	-2,76	-5,03	x
5	alloys	Raw	kg	0	x	0	x	x
6	aluminium (in ore)	Raw	kg	4,04	4,04	x	x	x
7	auxiliary materials	Raw	kg	0	x	0	x	x
8	barrage water	Raw	tn.lg	-113	x	-113	x	x
9	baryte	Raw	oz	77,3	76,1	0,0576	0,644	0,499
10	bauxite	Raw	lb	-90,3	190	-286	5,2	0,00373
11	bentonite	Raw	oz	103	101	0,0608	1,94	0,0673
12	boron (in ore)	Raw	mg	684	684	x	x	x
13	calcium sulphate	Raw	mg	19,3	19,3	x	x	x
14	calumite	Raw	g	-439	x	-439	x	x
15	chalk	Raw	pg	3,12E-13	3,12E-13	x	x	x
16	chromium (in ore)	Raw	g	1,37E3	574	0,0808	800	0,07
146	CFC-116	Air	mg	981	955	0,139	25,7	0,0184
147	CFC-12	Air	µg	26,5	10,7	x	11,6	4,2
148	CFC-13	Air	µg	16,6	6,75	x	7,25	2,64
149	CFC-14	Air	g	8,79	8,56	0,00112	0,231	0,000166
150	CFC (soft)	Air	µg	532	532	x	x	x
151	Cl2	Air	mg	99,4	99,4	x	x	x
152	CO	Air	oz	132	148	-18,2	2,22	0,209
153	CO2	Air	kg	1,53E4	1,56E4	-257	32,5	9,74
154	cobalt	Air	mg	897	891	0,518	4,46	1,14
155	Cr	Air	mg	807	802	0,501	4,54	0,727
156	CS2	Air	ng	380	380	x	x	x
157	Cu	Air	g	2,47	2,17	0,00125	0,302	0,00218
158	CxHy	Air	oz	311	339	-22,4	-5,76	x
159	CxHy aromatic	Air	mg	190	348	-123	-27,8	-7,19
284	COD	Water	oz	-34	1,7	-35,7	0,0274	0,0468
285	Cr	Water	g	31,8	30,3	0,00881	1,47	0,00939
286	Cr (VI)	Water	mg	7,98	7,94	0,00454	0,0322	0,00238
287	crude oil	Water	g	93,2	93,3	-0,0304	-0,0205	x
288	Cs	Water	mg	24,2	23,8	0,0134	0,157	0,162
289	Cu	Water	g	14,9	14,7	-0,00172	0,18	0,00596
290	CxHy	Water	g	621	620	0,273	0,462	0,000436
291	CxHy aromatic	Water	g	14,6	14,4	-0,0268	0,1	0,0938
292	CxHy chloro	Water	mg	13,1	13,1	0,0159	0,0363	-0,0035
293	cyanide	Water	mg	228	204	0,0119	23,2	0,558
294	detergent/oil	Water	mg	103	103	x	x	x
403	rejects	Solid	kg	0	x	0	x	x
404	slag	Solid	oz	298	298	0	0,000287	x
405	slags/ash	Solid	kg	23,9	23,9	x	x	x
406	soot	Solid	g	11,7	11,7	x	x	x
407	steel scrap	Solid	g	388	x	138	250	x
408	tinder from rolling drum	Solid	kg	0	x	0	x	x
409	unspecified	Solid	g	6,18	6,18	x	x	x
592	Zr65 to air	Non mat.	µBq	698	283	x	304	111
593	Zr65 to water	Non mat.	mBq	129	52,9	x	55,5	20,2
594	Zr95 to air	Non mat.	µBq	10,4	4,23	x	4,54	1,65
595	Zr95 to water	Non mat.	mBq	808	328	x	352	128

The simplification of the process tree in Figure 9.3b is a formal graphical representation of many processes in one box. The next steps in the LCA analysis require further *decomposition of the process tree* with respect to the importance of the environmental effects. The process tree can thus be simplified by performing a contribution analysis, in which processes of minor environmental importance are disregarded. As an example of decomposition, a process tree which includes only those processes which constitute more than 0.1% of the environmental index for the whole life cycle is shown (Figure 9.3c).

Application of other environmental criteria, e.g. damage category, impact category, etc. and the assumption of another level of environmental impact e.g. 0.5%, 1%, etc., leads to different forms for the process tree. As an example, Figure 9.3d shows a process tree for an aluminium window where the impact category is *Climate change* and the cut-off level 1%. For this category Eco-indicator 99 uses DALY (Disability Adjusted Life Years) as a unit which expresses damage to human health.

A comparison of Figures 9.3a to 9.3d shows different but complementary aspects of the life cycle of the aluminium window.

9.2.3 Analysing Process Trees

An analysis of all the process trees shows that extrusion of aluminium causes that the most important environmental impact. Its contribution to the total environmental load is over 95% in almost each impact category (compare the thickness of the lines in Figures 9.3c to 9.3d). In such a situation, when one process strongly dominates, the process tree can be considerably simplified (Figures 9.3c to 9.3d) which enables easier and more clear LCA.

9.2.4 Characterisation – Impact and Damage Categories

The next step in the LCA analysis is *characterisation*. This groups inflows and outflows into impact categories.

Inflows and outflows in the life cycle of an aluminium window were grouped in 11 impact categories according to the methodology of Eco-indicator 99. The characterisation shows the relative strength of the unwanted environmental impacts and their contributions to each environmental problem. Computational procedures used for aggregating the data into impact categories apply environmental models to compare different contributions to the same environmental problem. This task can be achieved using *equivalence factors* provided by the models.

An analysis of an inventory table for an aluminium window allow us to determine which substances contributes most importantly to each impact category. The 11 impact categories, each with the respective material from the life cycle of the ALU window, are as follows:

Carcinogens: these are mainly nickel, arsenic and cadmium as well as other metals released to water and air connected with electricity needed for extruding aluminium profiles, which is based on hard coal.

Respiratory substances: VOC (Volatile Organic Compounds) emissions, sulphur dioxide and nitric oxides resulting from aluminium alloy production, electricity generation and extrusion of aluminium.

Climate change: CO_2, NO_2 and methane emissions arising during aluminium extrusion and electricity production required for this process.

Radiation: Replacement of ferrules is of the highest significance, then, in turn, the manufacturing stage and the replacement of gaskets, which are connected with isotope emissions, mainly ^{14}C to the air and ^{137}Cs to water. The greatest contributions are ascribed to steel high alloy used in ferrule production and synthetic rubber for gaskets, both in the manufacturing life stage. For the production phase the outcome is presented as the summary contribution, whereas in the case of ferrules and gasket replacements, it is multiplied accordingly by 2 and 4 (multiple replacements during the entire life cycle).

Ozone layer: The outcome is almost entirely derived from HALON-1301 (CF_3Br) emitted in conjunction with electricity generation.

Ecotoxicity: mainly airborne emission of nickel and other metals caused by electricity production.

Acidification/eutrophication: nitric oxides and sulphur dioxide emissions connected with the extrusion of aluminium profiles and electricity production.

Land use: In this impact category the most important factor is the production of nuclear energy which is used as part of the electricity needed for aluminium extrusion.

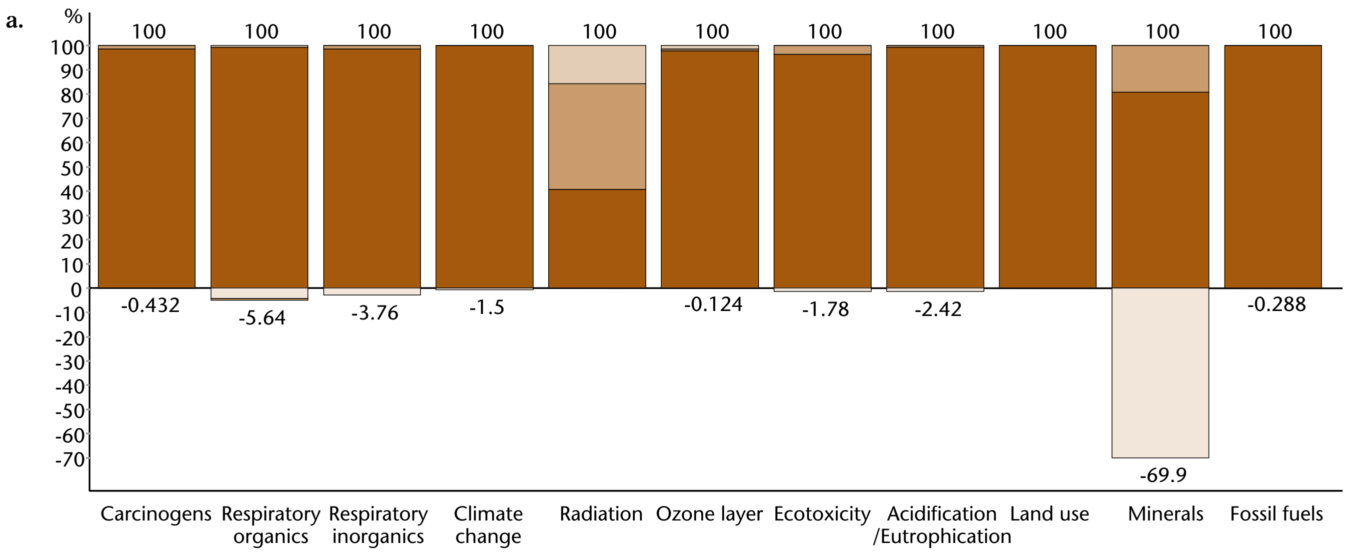
Minerals: Minerals depletion is influenced mainly by the production of aluminium alloy, out of which profiles are extruded, and higher quality steel for ferrules. Aluminium recycling is also of high significance. Aluminium scrap is treated as a raw material in aluminium production (such as bauxite). The environmental burden of the bauxite ore extraction is subtracted since it is avoided due to recycling.

Fossil fuels: Most of the fossil fuels (mainly crude oil and natural gas) are used in aluminium extrusion.

The characterisation thus amounts to a quantitative analyses of the effects of each phase of the life cycle for each impact category. The results are absolute values of impacts expressed in so-called effect scores or indices (Table 9.3). These constitute the environmental profile of the aluminium window.

Table 9.3 Environmental profile of the aluminium frame window. *The table shows the impact for each of 11 impact categories, generated by the SimaPro software. The results are expressed as effect score in DALY (Disability Adjusted Life Years) for categories influencing human health, in PDF (Potentially Disappeared Fraction) for categories influencing biodiversity and MJ (Mega Joules for surplus energy required for future acquisition) for resource consumption categories. The results are given for each of four life cycle processes, as well as the sum for the whole life cycle.*

Impact category	Unit	Total	ALU window	dismantling ALU wir	replacement of ferru	replacement of gask
Carcinogens	DALY	0,00113	0,00112	-4,91E-6	1,32E-5	1,73E-6
Resp. organics	DALY	1,67E-5	1,76E-5	-8,27E-7	-1,69E-7	7,62E-8
Resp. inorganics	DALY	0,00895	0,00919	-0,00035	0,000107	4,07E-6
Climate change	DALY	0,00355	0,0036	-5,43E-5	7,55E-6	2,15E-6
Radiation	DALY	9,88E-8	4,01E-8	x	4,31E-8	1,57E-8
Ozone layer	DALY	1,48E-6	1,44E-6	-1,84E-9	1,61E-8	1,65E-8
Ecotoxicity	PAF*m2yr	958	944	-17,3	29,5	2,08
Acidification/ Eutrophication	PDF*m2yr	321	326	-7,94	2,19	0,12
Land use	PDF*m2yr	598	597	0,169	0,716	0,135
Minerals	MJ surplus	28	74,9	-65	18	0,036
Fossil fuels	MJ surplus	2,53E4	2,53E4	-73,1	30,3	19,7



The results of the characterisation phase, shown as the relative significance of the life stages expressed in percent, is found in Figure 9.5a. The point of reference, 100%, is set equal to the sum for the entire life cycle. It is clear that the most important phase in the life cycle of an aluminium window is the manufacturing phase (dark brown colour). The impact of this phase covers almost 100% of the environmental load in 9 categories. It is caused by the high energy consumption in the aluminium extrusion process, emissions released in conjunction with electricity production, etc. Only in the impact categories *radiation* and *minerals* did the use phase and disposal phase show significant environmental impacts. Impacts in the use phase were caused by replacement of ferrules and gaskets, and in the disposal phase by the dismantling the ALU window. Note that the negative value of the impact in disposal phase in the minerals category comes from recycling of metals which diminishes the environmental load.

To obtain more transparent results of the LCA, let us group the 11 impact categories into three *damage categories* considered in Eco-indicator 99:

- *Human health:* carcinogens, respiratory inorganics, respiratory organics, climate change, radiation, ozone layer. The unit DALY (Disability Adjusted Life Years), which is used in this damage category, expresses different disabilities caused by diseases as well as years lost in consequence.
- *Ecosystem quality:* ecotoxicity, acidification/eutrophication, land use. The unit PDF·m^2·year (Potentially Disappeared Fraction) stands for the loss of species – decreased biodiversity.

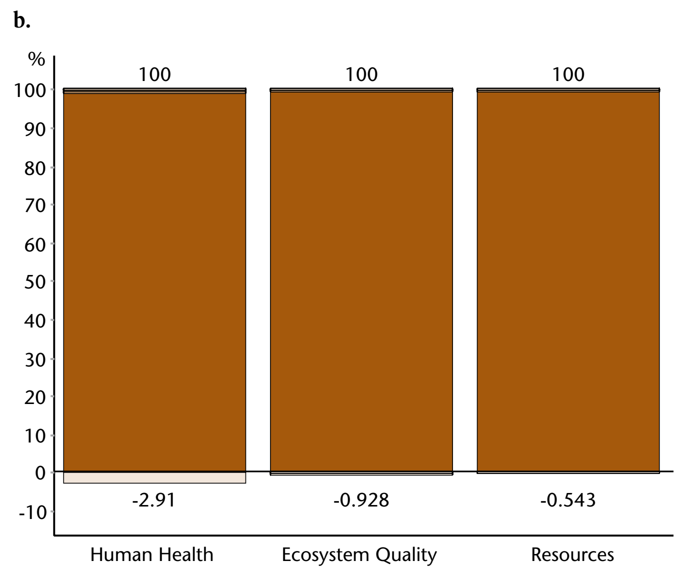


Figure 9.5 Life cycle impact assessment of the aluminium frame window for each life cycle phase. a. *The diagram shows the impact in 11 different impact categories calculated for one piece of window. The heights are 100% for the entire life cycle. The numerical values are percentage of total effect score in each impact category. impact factors.* **b.** *Impact for three damage categories. The numerical values are percentage of total effect score in each damage category. The method used was the Eco-indicator 99 (H) / Europe Ei 99 H/H using data for Europe.*

ALU window manufacturing | replacement of ferrules
dismantling ALU window | replacement of gaskets (ALU)

- *Resources:* minerals and fossil fuels. This damage is expressed in MJ surplus energy required for a future acquisition of minerals and fossil fuels.

Results of this aggregation are presented in Figure 9.5b. Analysis of Figure 9.5b confirms the conclusions from Figure 9.5a that the production phase causes the major environmental impact in the entire life cycle of the aluminium window.

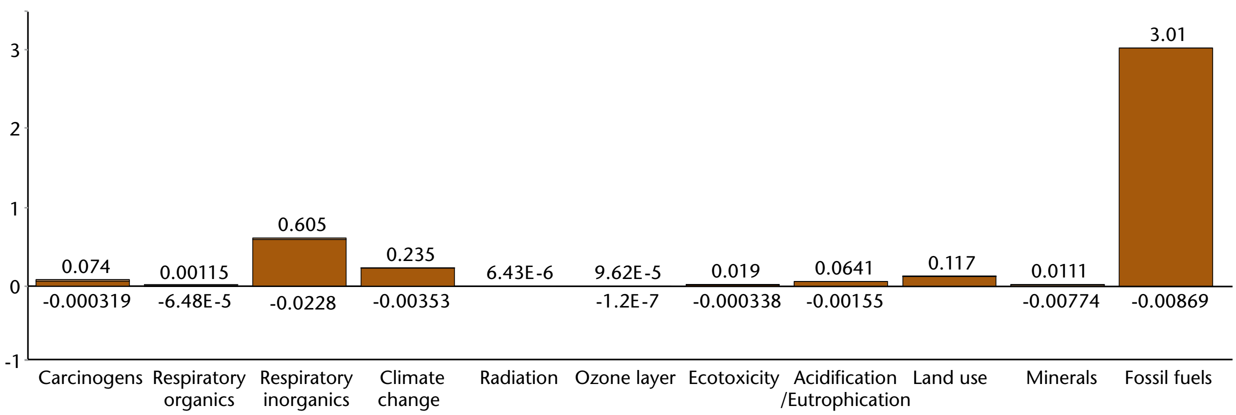
9.2.5 Normalisation

Normalisation is performed to make the effect scores of the environmental profile comparable. Normalised effect score is the ratio of an effect score for a given product annual contribution to that effect in a certain time over a certain area (compare for example Table 6.3 and Figure 6.3).

Eco-indicator 99 deals with normalisation by relating the environmental profile to the values representing the damage caused in the environment per inhabitant in given area (e.g. Europe), per year. To perform a normalisation process for all categories, all the impact must be multiplied by coefficients obtained from a statistical analysis of global emissions in a given area over the period of one year. For Eco-indicator 99 the impacts resulting in the deterioration of human health are multiplied by the factor of 65.1, in the deterioration of ecosystem quality by 1.95 10^{-4} and in the resources by 1.19 10^{-4}. The only exception constitutes ecotoxicity whose single score is multiplied by 0.1 before it is normalised. A detailed description of the coefficients applied in the method used is given in Table 9.4a.

The results of normalisation in the 11 impact categories (Figure 9.6a) shows that the biggest environmental burden associated with the life cycle of an aluminium window per inhab-

a.



a.

Impact category	Unit	Characterisation		Normalisation
Carcinogens	DALY	0.00113	* 65.1	0.0737
Resp. organics	DALY	1.67E-5	* 65.1	0.00109
Resp. inorganics	DALY	0.00895	* 65.1	0.583
Climate change	DALY	0.00355	* 65.1	0.231
Radiation	DALY	9.88E-8	* 65.1	6.43E-6
Ozone layer	DALY	1.48E-6	* 65.1	9.6E-5
Ecotoxicity	PAF*m2yr	958	*0.1 ; * 1.95 · 10^{-4}	0.0187
Acidification/ Eutrophication	PDF*m2yr	321	* 1.95 · 10^{-4}	0.0625
Land use	PDF*m2yr	598	* 1.95 · 10^{-4}	0.117
Minerals	MJ surplus	28	* 1.19 · 10^{-4}	0.00333
Fossil fuels	MJ surplus	2.53E4	* 1.19 · 10^{-4}	3.01

b.

Damage category	Unit	Characterisation		Normalisation
Human Health	DALY	0.0137	* 65.1	0.889
Ecosystem Quality	PDF*m2yr	1.01E3	* 1.95 · 10^{-4}	0.198
Resources	MJ surplus	2.53E4	* 1.19 · 10^{-4}	3.01

Table 9.4 Normalisation for the environmental impact of the aluminium frame window. a. *Effect scores after characterisation, normalisation coefficients and normalised effect scores for eleven impact categories.* **b.** *Effect scores after characterisation, normalisation coefficients and normalised effect scores for three damage categories. The method used was the Eco-indicator 99 (H) / Europe Ei 99 H/H using data for Europe.*

b.

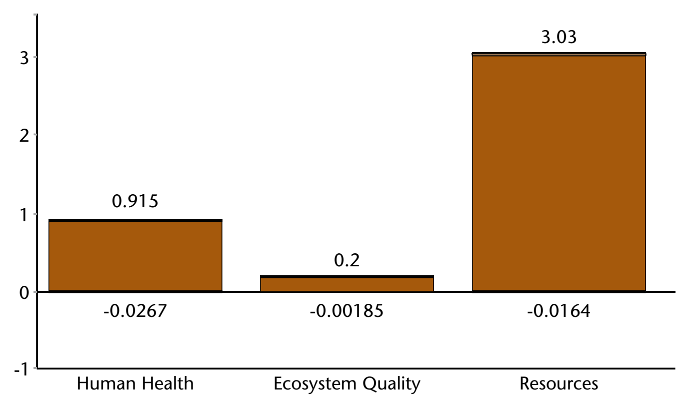


Figure 9.6 Normalisation of the environmental impact of the aluminium frame window for each life cycle phase. a. *Normalised effect scores for eleven impact categories divided into life cycle phases. Total values are found in Table 9.4a.* **b.** *Normalised effect scores for three damage categories divided into life cycle phases. Total values are found in Table 9.4b. The method used was the Eco-indicator 99 (H) / Europe Ei 99 H/H using data for Europe.*

ALU window manufacturing | replacement of ferrules
dismantling ALU window | replacement of gaskets (ALU)

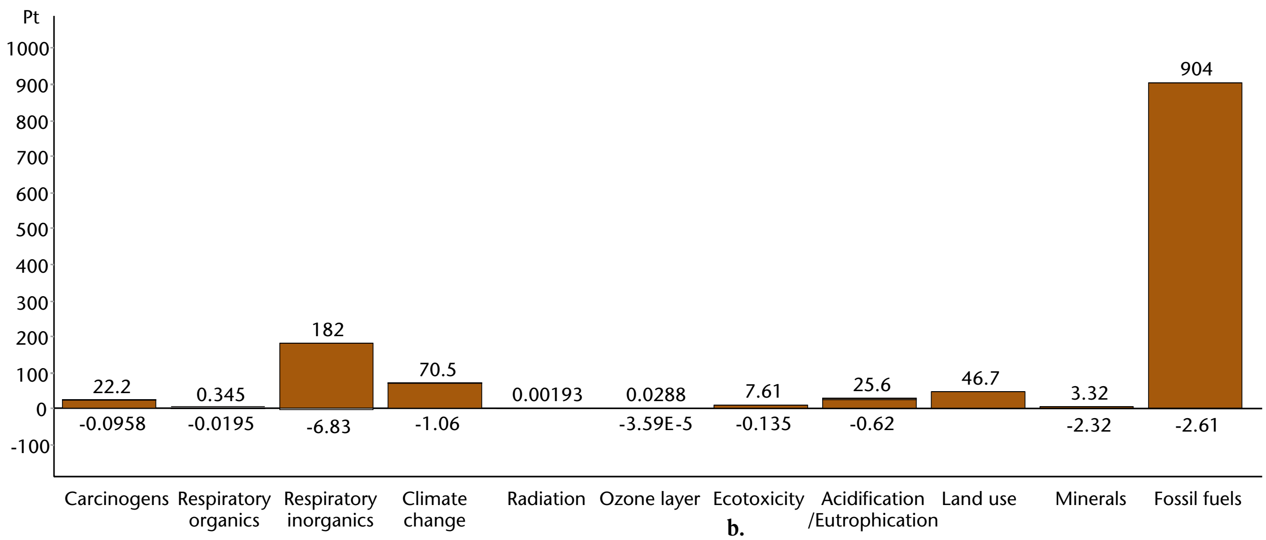
itant of Europe per year is attributed to the impact categories *fossil fuels* and *respiratory inorganic*. Similarly as in the characterisation phase, this result is ascribed to the production phase of an aluminium window (dark brown colour in Figure 9.6a).

The final results of the normalisation can also be expressed by aggregation of the impact categories into the three damage categories human health, ecosystem quality, and resources (Figure 9.6b).

Normalisation proved that the most important environmental impact in the life cycle of an aluminium window is the depletion of fossil fuels associated with aluminium extrusion. This has its greatest influence on the outcome for damage category *resources*. The next most important environmental impacts are from emissions of respiratory inorganic and greenhouse gases, both influencing human health.

Normalisation coefficients characteristic for selected damage categories are shown in Table 9.4b.

a.



a.

Impact category	Normalisation		Weighting
Carcinogens	0.0737	* 300	22.1
Resp. organics	0.00109		0.326
Resp. inorganics	0.583		175
Climate change	0.231		69.4
Radiation	6.43E-6		0.00193
Ozone layer	9.6E-5		0.0288
Ecotoxicity	0.0187	* 400	7.47
Acidification/ Eutrophication	0.0625		25
Land use	0.117		46.7
Minerals	0.00333	* 300	0.999
Fossil fuels	3.01		902

b.

Damage category	Normalisation		Weighting
Human Health	0.889	* 300	267
Ecosystem Quality	0.198	* 400	79.1
Resources	3.01	* 300	903

Table 9.5 Weighting for the environmental impact of the aluminium frame window. a. *Normalised effect scores, weighting coefficients and normalised and weighted effects scores, so-called eco-points for eleven impact categories.* **b.** *Normalised effect scores, weighting coefficients and normalised and weighted effects scores, so-called eco-points for three damage categories. The method used was the Eco-indicator 99 (H) / Europe Ei 99 H/H using data for Europe.*

b.

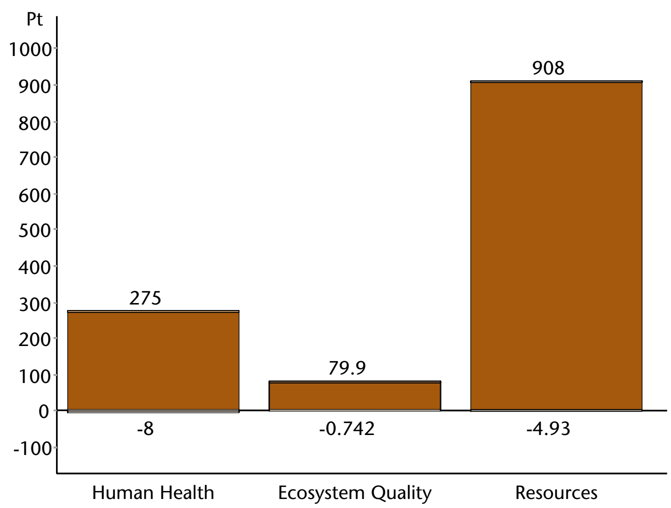


Figure 9.7 Weighting of the environmental impact of the aluminium frame window for each life cycle phase. a. *Normalised and weighted effect scores, so-called eco-points (Pt) for eleven impact categories divided into life cycle phases.* **b.** *Normalised and weighted effect scores, so-called eco-points (Pt) for three damage categories divided into life cycle phases. The method used was the Eco-indicator 99 (H) / Europe Ei 99 H/H using data for Europe.*

ALU window manufacturing; replacement of ferrules; dismantling ALU window; replacement of gaskets (ALU)

9.2.6 Weighting

Weighting is the step in which the different impacts categories are weighted for comparison between themselves, i.e. the relative importance of the effects is assessed. Weighting allows us to arrive at one single score representing the environmental impact of a product.

Like normalisation, the weighting process is performed on the damage assessment level by multiplying a normalised environmental profile by a set of weighting factors, which reflect the seriousness of a given effect (assessed by an expert panel, Box 6.1).

In Eco-indicator 99 the following *weighting factors* are attributed to the damage categories:

- Human health 300
- Ecosystem quality 400
- Resources 300

Selection of weighting factors in Eco-indicator 99, which is based on local preferences and social values, rates the ecosystem (400) higher than human health and resources, whose seriousness has been assessed to be equal (300). Multiplication of normalisation coefficients by weighting factors gives single scores for each category (Table 9.5a). The normalised and weighted effect score is called eco-points in the Eco-indicator 99 model and is expressed as points (Pt). A graphical representation of the result of the calculations is shown in Figure 9.7a.

Comparing the results of normalisation and weighting phases, we may conclude that the general outcome is similar. The most significant environmental burden is ascribed to impact categories *fossil fuels* and *respiratory inorganics* (caused by the manufacturing phase, dark brown colour for *ALU window*). The only difference between the normalisation and weighting phases is the proportion between the impacts. This difference is the result of the assumption of weighting coefficients which give priority to ecosystem quality over human health and resource depletion. Figure 9.7a also shows negative values of particular impacts. Negative values represent these inflows and outflows which are not released to the atmosphere due to recycling and energy recovery.

The results of the weighting phase can be also analysed for damage categories (Figure 9.7b). Weighting coefficients characteristic of selected damage categories and final results of weighting are shown in Table 9.5a. Weighting did not change significantly the proportions between damage categories. Nevertheless, resource depletion resulting from the production phase dominates.

9.2.7 Single Score

Eco-indicator 99 is one of the methods which allow us to arrive at one single score for the entire life cycle – a so-called *environmental index*, or environmental score, both expressions are used. This is the sum of all individual eco-points or partial indices for all life cycle processes. The computational procedure is performed by adding up the results of weighting within life cycle phases (production phase – *ALU window*, disposal phase – *dismantling ALU window* and use phase – *replacement of ferrules* and *replacement of gasket*). The results can

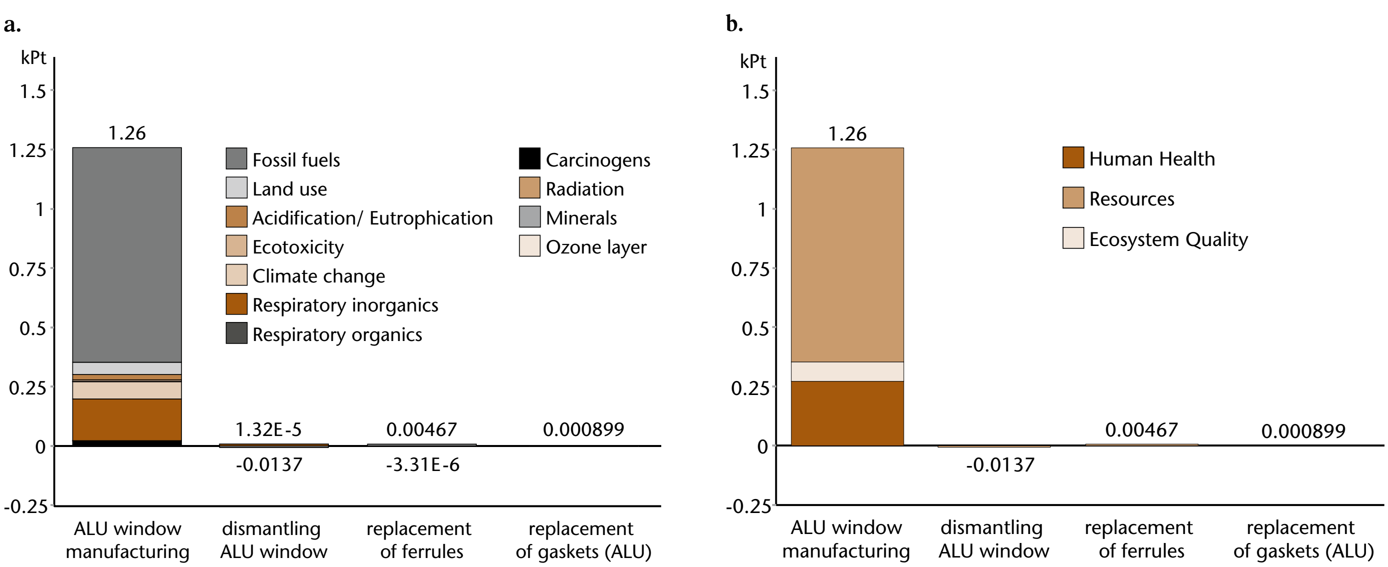


Figure 9.8 Environmental scores (indices) for the life cycle of the aluminium frame window for four life cycle functions. a. *The colour code shows 11 impact categories. Fossil fuel use is the dominating one.* **b.** *The colour code shows the three damage categories human health, resource use and ecosystem quality. The numerical values are total eco-points or indices for all partial process. The grand total for the aluminium frame window is 1260 eco-points, here expressed in thousand points (kPt). The method used was the Eco-indicator 99 (H) / Europe Ei 99 H/H using data for Europe.*

be displayed for damage categories (Figure 9.8a) or for impact categories (Figure 9.8b). The environmental index is thus 1260 eco-points.

Almost 100% of the single score in case of an aluminium window is allocated over the production phase (ALU window). Manufacturing of an aluminium window affects mostly human health and resource depletion (Figure 9.8a). The negative values calculated for the final disposal comes from metals and glass recycling. The same analysis for impact categories shows the highest scores in *fossil fuels* and *respiratory inorganics* categories.

9.3 PVC Window LCA

9.3.1 Life Cycle Inventory

The LCA analysis for a PVC window was performed in identical way as for the ALU window. Illustration of the first step in the LCA, the Life Cycle Inventory for the PVC window (Figure 9.9) displays inflows and outflows for all life cycle phases of the PVC window.

As in the case of the ALU window, all the technical data were collected from companies installing windows in Lodz, Poland.

Basic technical data collected for the LCA analysis of the PVC window are displayed in Table 9.5b.

The total mass of the PVC window is 67.4 kg. Of this, 24.2 kg is the weight of the PVC profiles and other PVC ele-

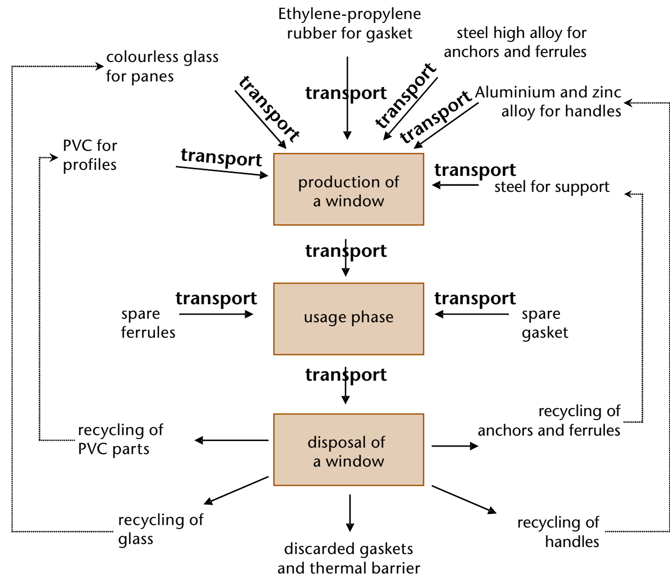


Figure 9.9 Inventory of inflows and outflows. *The inventory diagram for the life cycle of the PVC frame window.*

Table 9.6 Technical data for LCA of the PVC window. *Data shown for white PVC profile. The weight of other elements are estimated to be only few grams and is thus neglected. The weight of the support is estimated to be 0.85 kg/running meter. The weight of the gasket is estimated to be 0.015 kg/running meter. The glass is estimated to be 1 mm thick and have a total weight of 2.5 kg/m². The weight of the ferrule is estimated to be 2.5 kg and the anchors 0.25 kg.*

White PVC profile			
Element	Length (m)	Mass of running meter (kg)	Mass of the element (kg)
Frame	5.8	1.4	8.12
Muntin	1.4	1.68	2.352
Sashes	8.2	1.43	11.729
Sash stop	7.3	0.25	1.825
Other elements (estimated)			~ 0
Total			24.0

Other elements and accessories			
Name	Material	Quantity	Mass (kg)
Support	Carbon steel S 10	14 m	11.9
Gasket	Ethylene-propylene rubber (EPDM)	~ 16.4 m	0.25
Panes	Colourless glass	Two double integrated panes 4/16/4 of size 561x1241.	27.8
Ferrules and anchors	High-quality steel	1 set	2.75
Handles	Aluminium and zinc alloy (ZnAl)	1 set	0.5
Total			43.2

ments. Main PVC profiles are imported from a factory near Berlin. The road distance is around 600 km. Particular elements are produced by extrusion.

Metal sections for supports are made of steel and have a total weight of 11.9 kg. They are transported from Katowice through Wrocław, a distance of 400 km.

Ferrules, made of high quality steel, weigh 2.75 kg. They are imported from Austria via Czekanów (600 km).

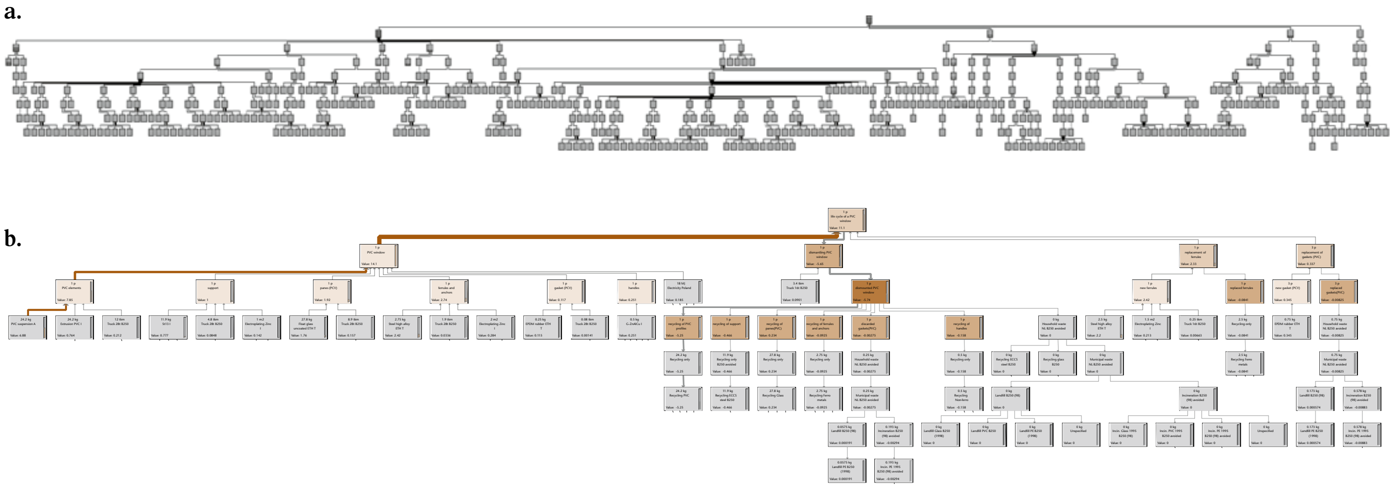
The glass, with a total weigh of 27.8 kg, is the *float* type produced in Sandomierz (Poland). It is integrated hermetically into window panes in Czestochowa (distance 320 km).

Other material includes the handles made of zinc aluminium alloy (0.5 kg) and some plastics.

During 40-year use the window requires one replacement of ferrules (after around 20 years) and three replacements of gaskets (every 10 years). These elements have their own life cycles. The replaced ferrules are scrapped and gaskets are discarded. After 40 years, a window is dismounted. Plastic elements, supports, handles, ferrules, anchors and panes can be recycled. The rest, i.e. gaskets, are discarded, partly incinerated and partly land filled (according to a Dutch scenario of municipal waste utilisation). Instead of dividing the transport according to particular groups of objects, it was assumed that the whole window is transported a distance of 50 km.

Due to the lack of sufficient data, the following effects have been neglected:

- Window cleaning.
- Elements necessary for glass integration (small amounts of butyl, thioplast and aluminium frames).



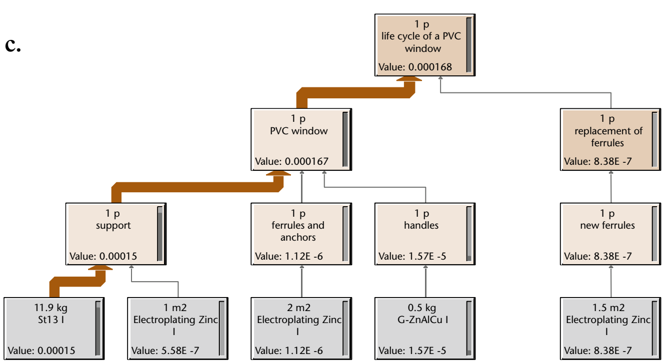


Figure 9.10 Process trees for and LCA of the PVC frame window. a. *Full process tree for a life cycle of the PVC frame window generated by SimaPro.* **b.** *Simplified process tree in which several processes are grouped into one box. This includes environmental indices calculated according to Eco-indicator 99. The thickness of the lines is proportional to the environmental impact.* **c.** *Simplified process tree in which only elements with an environmental index larger that 0.1% for the impact category VOC emissions is included.*

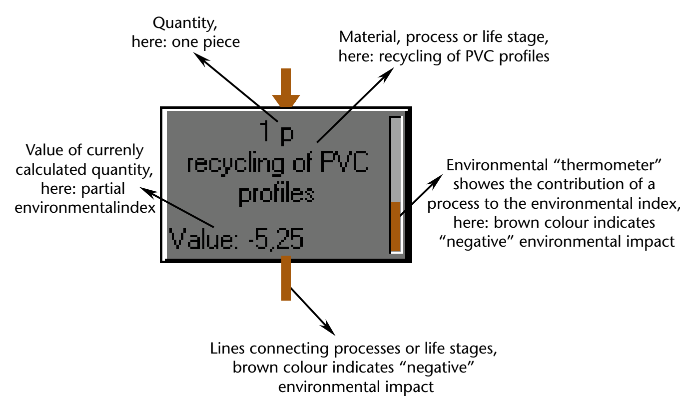


Figure 9.11 A process box for the calculation of an environmental index. *The calculation is made for an item in the life cycle of the PVC frame window. The process box contains the life stage, the material, the quantity, the environmental index for that impact, and the thermometer showing the contribution of the process to the total environmental index.*

9.3.2 Process Trees

The full process tree for the PVC window, developed by the software SimaPro, is shown in Figure 9.10a. The grey boxes in the figure schematically represent subsequent technological processes grouped into life phases (production, usage, disposal). The figure shows that the life cycle of a PVC window is as complex as that of an aluminium window (Figure 9.3a).

As in the previous analysis, certain inflows and outflows were grouped in only one box. An example of a simplified process tree for the PVC window (Figure 9.10b) shows environmental indexes of the life cycle phases calculated according to the Eco-indicator 99 method. The thickness of lines graphically illustrates the level of environmental impact of particular processes constituting a life cycle of the PVC window.

A process box for calculation of environmental index is shown in Figure 9.11. Negative values in the box result from emissions avoided due to recycling or energy recovery.

The process tree shown in Figure 9.10b can be further simplified to exclude the weak influence of certain processes in the life cycle, for example, if considering volatile organic compounds (VOC) emissions, after omitting components that contribute less than 0.1% of all VOC emissions (Figure 9.10c).

The values in the boxes of the process tree represent the mass emitted in the different technological process expressed in kilos. Nearly 90% of the VOC emissions in the life cycle of a plastic window come from the manufacturing of the steel sections which are used as the window profile support. It is worth noting that unwanted emissions of VOC are not connected with the production of steel itself but with the transportation of steel by bulk carriers which run on heavy fuel oil.

Similar modifications of the process tree can be obtained by setting up different cut-off rules.

For the PVC window the full inventory table consists of 588 items. A huge number of inflows and outflows thus occur during the PVC window life cycle. Collection and data quality assessment are the first and crucial steps to develop reliable LCA for any products or systems. Selected items of an inventory table for the life cycle of the PVC frame window are shown in Table 9.7.

Table 9.7 Inventory table for the life cycle of the PVC frame window. *The table is generated by the SimaPro software and its database and contains 588 entries.*

No	Substance	Comp	Unit	Total	PVC window	dismantling PVC	replacement of f	replacement of g
1	acids	Raw	g	14,9	x	14,9	x	x
2	additions	Raw	g	-47,5	x	-47,5	x	x
3	additives	Raw	g	-355	x	-355	x	x
4	air	Raw	oz	181	186	-2,76	-2,51	x
5	alloys	Raw	g	6,19	x	6,19	x	x
6	auxiliary materials	Raw	g	137	x	137	x	x
⋮								
8	baryte	Raw	g	66,1	30,5	21,2	9,13	5,3
9	bauxite	Raw	oz	91,1	48,2	1,24	41,6	0,0224
10	bentonite	Raw	g	86	35,4	22,4	27,5	0,715
⋮								
141	CFC-114	Air	mg	2,12	1,22	x	0,708	0,193
142	CFC-116	Air	mg	29,3	14,8	1,67	12,9	0,0069
143	CFC-12	Air	µg	17,3	9,94	x	5,78	1,58
144	CFC-13	Air	µg	10,9	6,24	x	3,62	0,99
145	CFC-14	Air	mg	262	133	13,3	116	0,0621
⋮								
277	Cl-	Water	oz	209	229	-25,3	3,73	1,26
278	Cl2	Water	mg	42,3	42,3	x	x	x
279	Co	Water	mg	110	43,2	45,1	20,9	0,877
280	COD	Water	g	-2,36	20	-23,2	0,388	0,497
281	Cr	Water	g	2,28	1,48	0,0617	0,736	0,00352
282	Cr (VI)	Water	µg	109	33,2	59,1	16,1	0,892
⋮								
398	slag	Solid	oz	-126	0,0457	-127	0,000143	x
399	slags/ash	Solid	oz	-27,2	8,9	-36,1	x	x
400	steel scrap	Solid	g	263	x	138	125	x
401	tinder from rolling drum	Solid	g	-109	x	-109	x	x
402	unspecified	Solid	mg	213	213	x	x	x
403	waste bioactive landfill	Solid	kg	0	x	0	x	x
⋮								
585	Zn65 to air	Non mat.	µBq	455	262	x	152	41,5
586	Zn65 to water	Non mat.	mBq	84,2	48,9	x	27,8	7,57
587	Zr95 to air	Non mat.	µBq	6,8	3,91	x	2,27	0,62
588	Zr95 to water	Non mat.	mBq	527	303	x	176	47,9

9.3.3 Characterisation

The characterisation phase for the PVC window was performed in an identical way as for the aluminium window, including computational procedures used for aggregating the data and by application of identical equivalence factors (Table 6.2).

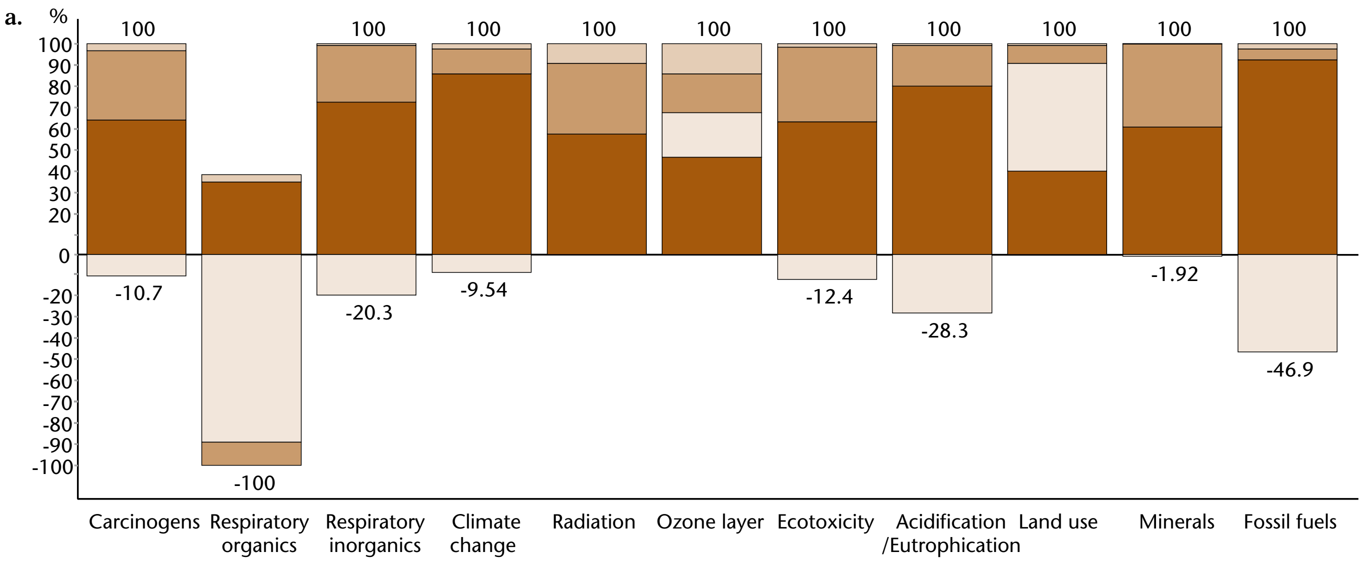
The results of a characterisation phase are absolute values of impacts expressed in effect scores or indices (not shown, but compare Table 9.3). The relative values in percentage for the total for each life cycle phase for the eleven impact and three damage categories are graphically presented in Figure 9.12.

The analysis shows that the manufacturing phase of the PVC window produces the biggest impact in the life cycle of the window (dark brown colour), although this effect is not as significant as in the case of the aluminium window (compare Figure 9.5). The use phase (especially replacement of ferrules and window dismantling) covers a substantial part of the environmental load in several impact categories. In the impact categories r*espiratory organics* and *fossil*, high negative values in the disposal phase are due to efficient technology of PVC recycling.

Deeper analysis of an inventory table for the PVC window indicates that the following substances have the most significant contributions for each impact category:

Carcinogens: These include mainly nickel, arsenic and cadmium emitted to water and air. They are involved in the production of steel for ferrules and profile supports as well as glass. During the utilisation phase, the highest negative values are recorded, from recycling handles and supports, and the positive ones – from producing electricity necessary for PVC and glass recycling. However, the final result for *dismounting* is negative.

Respiratory organics: Emissions of volatile organic substances (excluding methane) and ethylene accompany mainly PVC production and extrusion. However, negative emissions of hydrocarbons of general formula C_XH_Y obtained by recycling of PVC and ferrules, prevail.



Respiratory inorganics: These are primarily emissions of sulphur and nitric oxides related mainly to the production of steel and PVC, and also negative emissions of dust during PVC recycling.

Climate change: Over 90% of results in this category include CO_2 emissions generated during the production of electricity necessary for recycling and for the production of PVC by the suspension technique, and the production of steel for ferrules and of glass. Negative emissions for the terminal phase of the life cycle are a result of window profile supports recycling.

Radiation: The greatest contributions are from the processes of production of steel for ferrules, glass, and synthetic rubber for gaskets. For the production stage the result is represented by a total contribution of these processes, while in the replacement of ferrules and gaskets it is multiplied (multiple replacement).

Ozone layer: HALON 1301 (CF_3Br) emitted during steel and gasket production is almost entirely responsible for the result in this category. Dismantling of a window has a positive contribution in this category because of the production of electricity needed for recycling.

Ecotoxicity: The most important substances toxic for the environment in the life cycle of a plastic window are nickel, zinc, and copper, as well as other emissions to the atmosphere. The emissions are induced by the production of steel for ferrules. Negative emissions are related to the recycling of handles and panes (negative lead and cadmium emissions).

Acidification/eutrophication: Noteworthy in this category are emissions of nitric oxides and sulphur dioxide connected with the production of steel for ferrules, PVC and electricity. The negative result for the phase of window utilisation was obtained by the recycling of plastic profiles and supports.

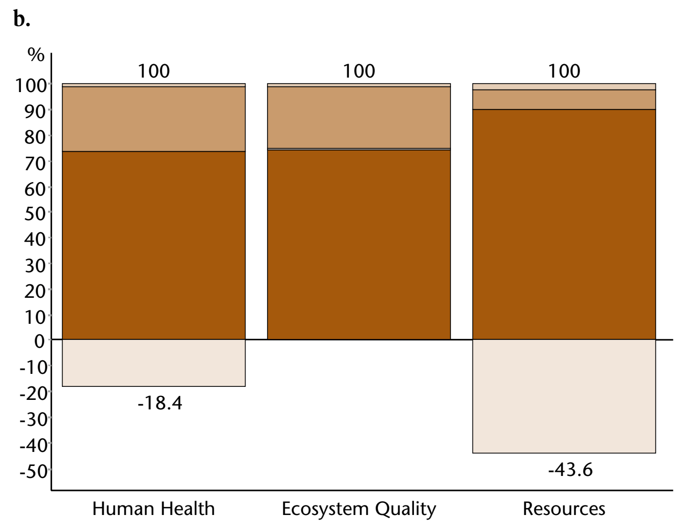


Figure 9.12 Life cycle impact assessment of the PVC frame window for each life cycle phase. a. *The diagram shows the impact in 11 different impact categories calculated for one piece of window. The heights are 100% for the entire life cycle. The numerical values are percentages of total effect score in each impact category.* **b.** *Impact for three damage categories. The numerical values are percentages of total effect score in each damage category. The method used was the Eco-indicator 99 (H) / Europe Ei 99 H/H using data for Europe.*

PVC window manufacturing · replacement of ferrules · dismantling PVC window · replacement of gaskets (PVC)

Land use: The greatest impact on the environment has the production of electric energy for recycling and transport of steel by bulk cargo ships.

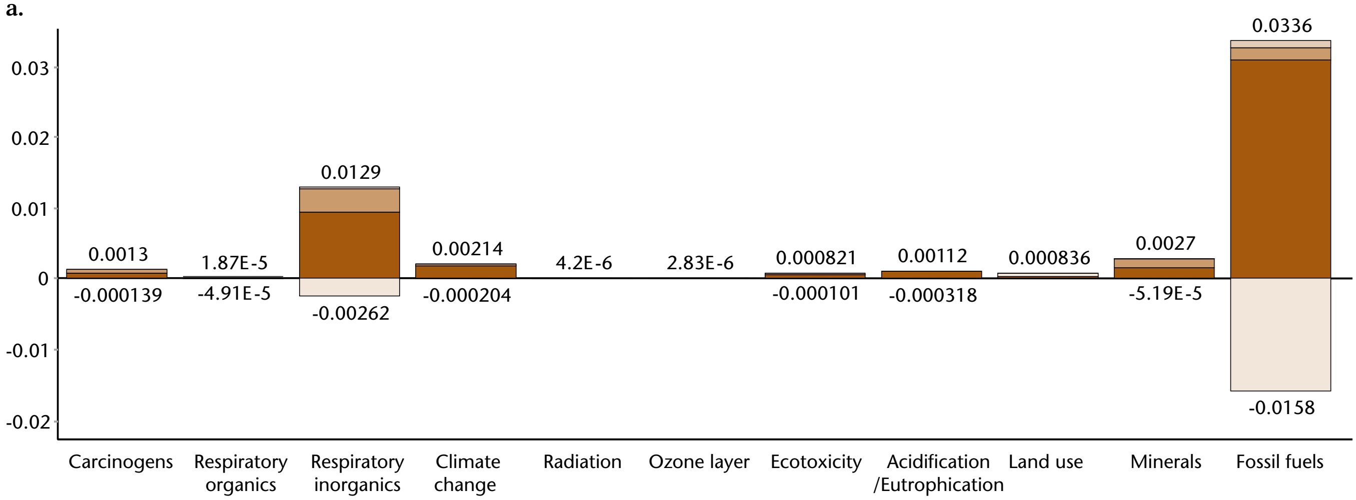
Minerals: The consumption of minerals depends greatly on the production of high-quality steel for ferrules and anchors (mainly nickel and zinc). Recycling of metal parts makes it possible to avoid mining of iron and zinc ores.

Fossil fuels: In the phase of production, the most crude oil and natural gas is used. Processes that are most important include the production of PVC and electric energy. The negative fuel consumption which occurs in the phase of window dismantling is a result of PVC recycling.

As before the results can be aggregated into three damage categories; human health, ecosystem quality and depletion of natural resources. Carcinogens, compounds that cause respiratory diseases, greenhouse effect, radiation, and depletion of ozone layer contribute to the deterioration of human health. Compounds toxic to the environment, eutrophication, acidification and extension of areas occupied by man deteriorate the conditions of life of many species on Earth (ecosystem quality), while consumption of minerals and fossil fuels reflects depletion of natural resources. From the figure it follows that for each end point, the most harmful stage in PVC window life cycle is the production phase (dark brown colour, Figure 9.12b).

Analysing the results in damage categories, we may also conclude that by recycling of PVC, the impact of the window life cycle on human health, and resource depletion are substantially reduced (see negative values in Figure 9.12b, dismantling of PVC window).

a.



a.

Impact category	Unit	Characterisation		Normalisation
Carcinogens	DALY	1.78E-5	* 65.1	0.00116
Resp. organics	DALY	-4.68E-7	* 65.1	-3.04E-5
Resp. inorganics	DALY	0.000157	* 65.1	0.0102
Climate change	DALY	2.98E-5	* 65.1	0.00194
Radiation	DALY	6.45E-8	* 65.1	4.2E-6
Ozone layer	DALY	4.34E-8	* 65.1	2.83E-6
Ecotoxicity	PAF*m2yr	36.9	* 0.1 * $1.95 \cdot 10^{-4}$	0.00072
Acidification/ Eutrophication	PDF*m2yr	4.13	* $1.95 \cdot 10^{-4}$	0.000805
Land use	PDF*m2yr	4.29	* $1.95 \cdot 10^{-4}$	0.000836
Minerals	MJ surplus	22.3	* $1.19 \cdot 10^{-4}$	0.00265
Fossil fuels	MJ surplus	150	* $1.19 \cdot 10^{-4}$	0.0178

b.

Damage category	Unit	Characterisation		Normalisation
Human Health	DALY	0.000205	* 65.1	0.0133
Ecosystem Quality	PDF*m2yr	12.1	* $1.95 \cdot 10^{-4}$	0.00236
Resources	MJ surplus	172	* $1.19 \cdot 10^{-4}$	0.0205

Table 9.8 Normalisation for the environmental impact of the PVC frame window. a. *Effect scores after characterisation, normalisation coefficients and normalised effect scores for eleven impact categories.* **b.** *Effect scores after characterisation, normalisation coefficients and normalised effect scores for three damage categories. The method used was the Eco-indicator 99 (H) / Europe Ei 99 H/H using data for Europe.*

b.

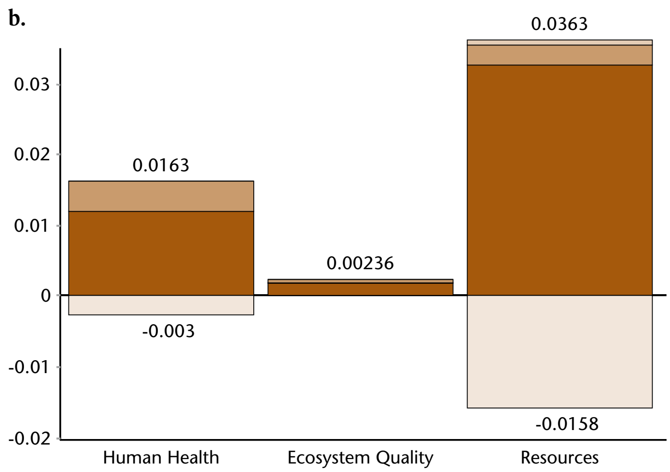


Figure 9.13 Normalisation of the environmental impact of the PVC frame window for each life cycle phase. a. *Normalised effect scores for eleven impact categories divided into life cycle phases. Total values are found in Table 9.8a.* **b.** *Normalised effect scores for three damage categories divided into life cycle phases. Total values are found in Table 9.8b. The method used was the Eco-indicator 99 (H) / Europe Ei 99 H/H using data for Europe.*

PVC window manufacturing | replacement of ferrules
dismantling PVC window | replacement of gaskets (PVC)

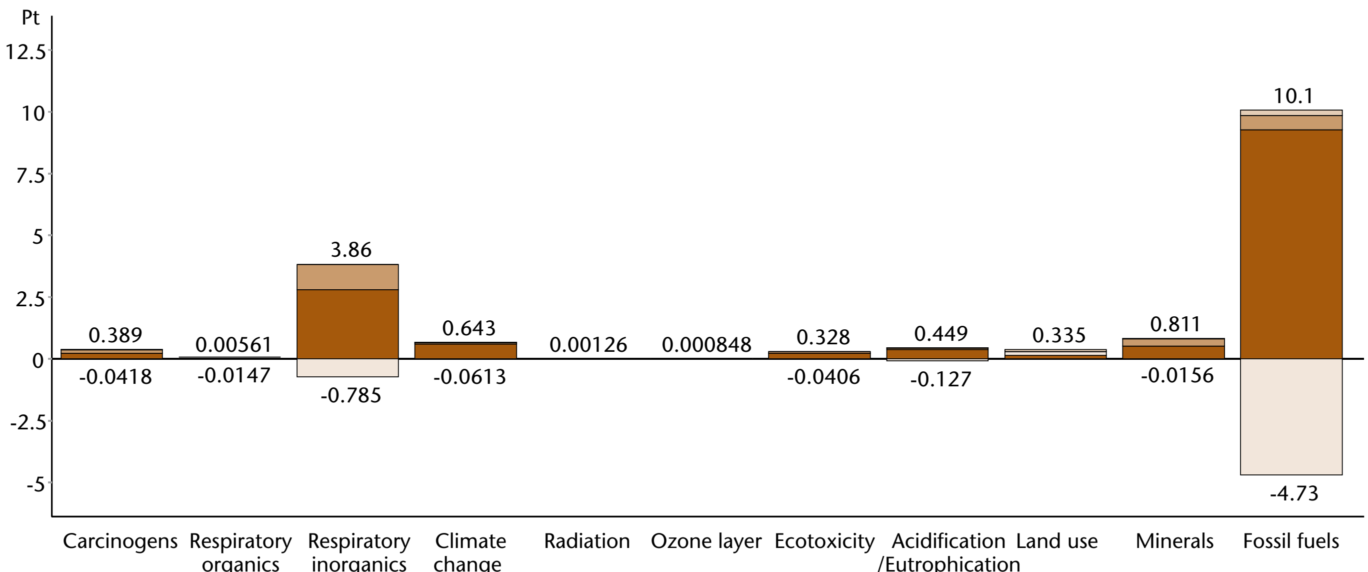
9.3.4 Normalisation

To make the environmental profiles comparable, the results achieved in characterisation phase must be normalised. The results of the characterisation are then multiplied by values reflecting the damage caused in the environment per inhabitant (e.g. of Europe), per year (Table 6.1).

Results of normalisation of PVC window life cycle are presented in Figure 9.13a. The calculations of the normalisation parameters are shown in Table 9.8a (according to Eco-indicator 99 methodology; for details, see previous section).

As can be easily seen, the life cycle of the plastic window contributes mostly to the depletion of fossil fuels (for the production of the PVC suspension) and emissions of respiratory inorganic compounds such as SO_x or NO_x (production of steel high alloy). Figure 9.8b shows the results of normalisation on the midpoints level, i.e. in impact categories. As in the LCA

a.



a.

Impact category	Normalisation		Weighing
Carcinogens	0.00116		0.347
Resp. organics	-3.04E-5		-0.00913
Resp. inorganics	0.0102	* 300	3.07
Climate change	0.00194		0.581
Radiation	4.2E-6		0.00126
Ozone layer	2.83E-6		0.000848
Ecotoxicity	0.00072		0.288
Acidification/ Eutrophication	0.000805	* 400	0.322
Land use	0.000836		0.335
Minerals	0.00265	* 300	0.796
Fossil fuels	0.0178		5.35

b.

Damage category	Normalisation		Weighting
Human Health	0.0133	* 300	4
Ecosystem Quality	0.00236	* 400	0.944
Resources	0.0205	* 300	6.15

Table 9.9 Weighting for the environmental impact of the PVC frame window. a. *Normalised effect scores, weighting coefficients and normalised and weighted effects scores, so-called eco-points for eleven impact categories.* **b.** *Normalised effect scores, weighting coefficients and normalised and weighted effects scores, so-called eco-points for three damage categories. The method used was the Eco-indicator 99 (H) / Europe Ei 99 H/H using data for Europe.*

b.

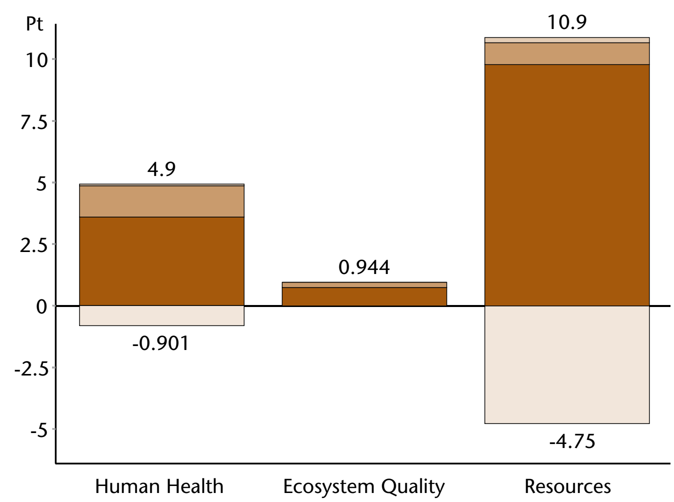


Figure 9.14 Weighting of the environmental impact of the PVC frame window for each life cycle phase. a. *Normalised and weighted effect scores, so-called eco-points (Pt) for eleven impact categories divided into life cycle phases.* **b.** *Normalised and weighted effect scores, so-called eco-points (Pt) for three damage categories divided into life cycle phases. The method used was the Eco-indicator 99 (H) / Europe Ei 99 H/H using data for Europe.*

PVC window manufacturing; replacement of ferrules; dismantling PVC window; replacement of gaskets (PVC) of the ALU window, the final results of the normalisation can be also be expressed in damage categories by aggregation of impact categories into three groups: human health, ecosystem quality, and resources (Figure 9.13b). The procedures used to determine normalisation values in damage categories are shown in Table 9.8b.

Figure 9.13b and Table 9.8b show that the life cycle of the PVC window contributes strongly to the depletion of raw materials and to deterioration of human health. The influence of the plastic window life cycle on the deterioration of ecosystem quality is almost 10 times less than on resource depletion (Table 9.8b, last column).

9.3.5 Weighting

In the weighting step, different impacts and damage categories are weighed to be compared among themselves, i.e. to asses the relative importance of the effects and finally to obtain one single score representing the environmental impact of the product.

Weighting factors, which reflect the seriousness of a given effect selected according to Eco-indicator 99 methodology are identical for the LCA and ALU windows:

- Human health 300
- Ecosystem quality 400
- Resources 300

Results of this step of the LCA analysis are shown in Figure 9.14a and in Table 9.9a The results of normalisation and weighting phases are similar, i.e. the most serious environmental burden is ascribed to impact categories *fossil fuels* and *respiratory inorganics* (5.35 and 3.07 respectively, Table 9.9a) caused by the production phase (dark brown colour). The difference between the normalisation and weighting phases is the proportion between the impacts, due to the priority of ecosystem quality over human health and resources depletion. Negative values in Figure 9.14a and Table 9.9a represent inflows and outflows which are not released to the atmosphere due to recycling and energy recovery.

The results of the weighting phase were also calculated for damage categories (Figure 9.14b). Weighting coefficients characteristic for the three damage categories and final results of weighting are shown in Table 9.9b. The results of weighting did not change the normalisation results appreciably. However, the ratio between deterioration of ecosystem quality and resource depletion is equal now, about 7 (6.15/0.944, Table 9.9b, last column) while in the normalisation phase it was about 10. This result comes from the assumption of priority of ecosystem quality (400) over human health (300) and resources depletion (300), (Table 9.9b).

9.3.6 Single Score

Eco-indicator 99 allows us as before to obtain an *environmental index*, for the entire life cycle of products or services for damage categories (Figure 9.15a) or for impact categories (Figure 9.15b). The environmental index is calculated by summing up

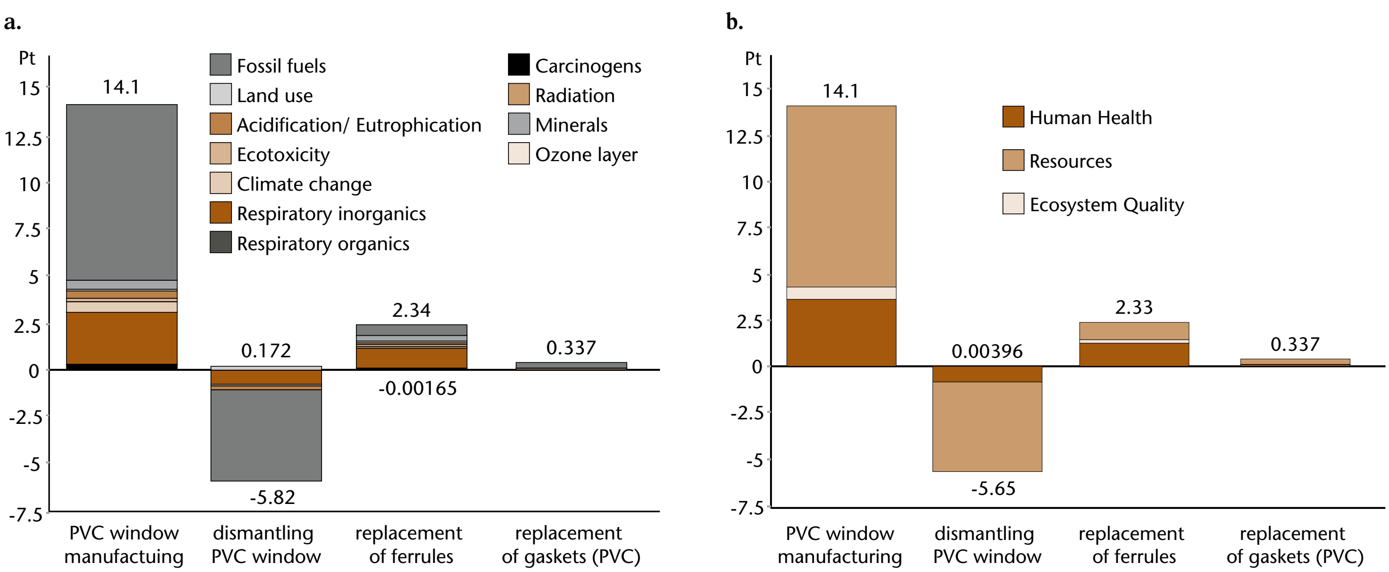
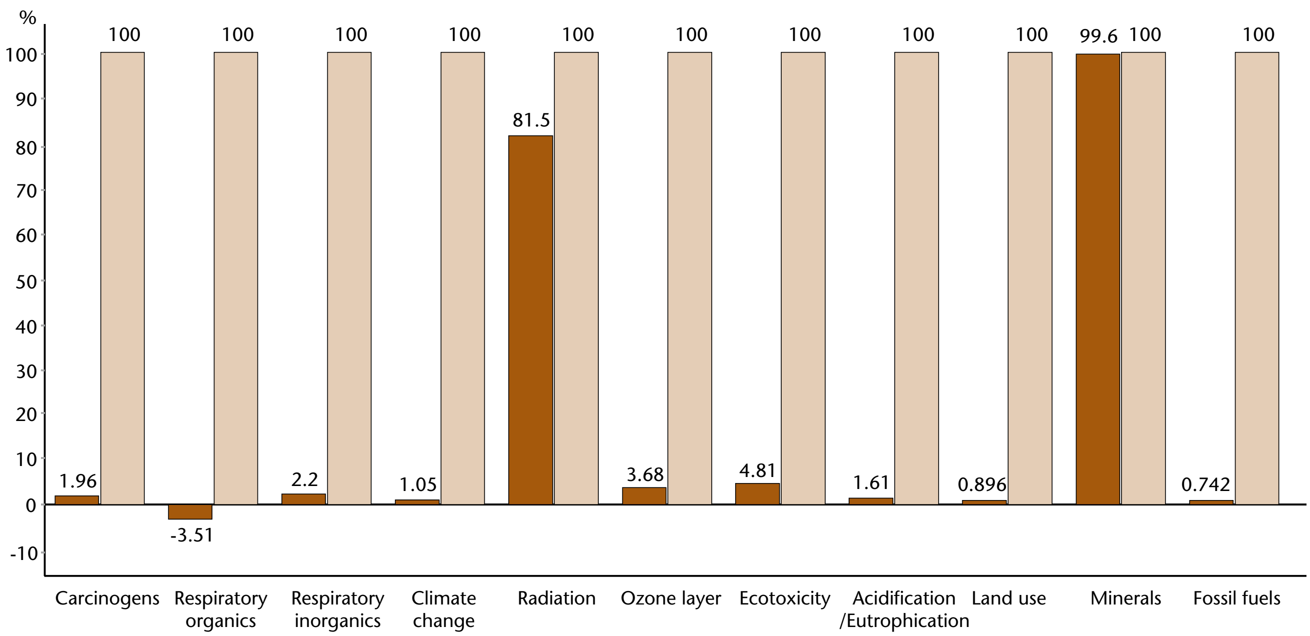


Figure 9.15 Environmental scores (indices) for the life cycle of the PVC frame window for four life cycle functions. a. *The colour code shows 11 impact categories. Fossil fuel use is the dominating one.* **b.** *The colour code shows the three damage categories human health, resource use and ecosystem quality. The numerical values are total eco-points or indices for all partial process. The grand total for the PVC frame window is 11.1 eco-points, expressed in points (Pt). The method used was the Eco-indicator 99 (H) / Europe Ei 99 H/H using data for Europe.*

a.



b.

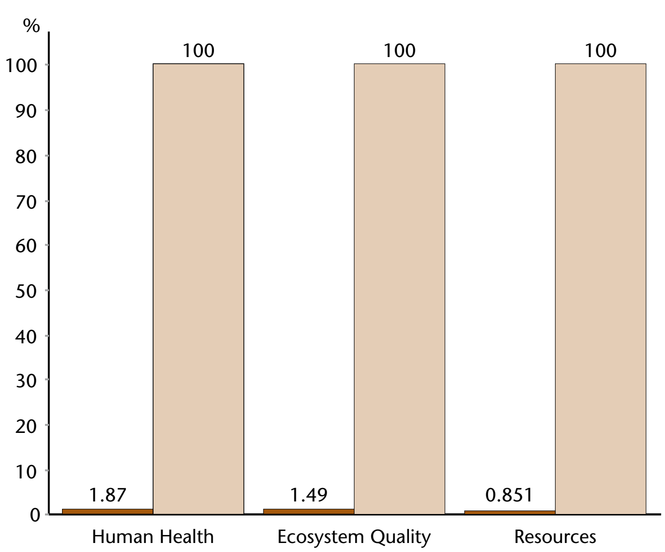


Figure 9.16 Comparative analysis of the Aluminium and PVC frame windows – characterisation. *The LCA of the two windows are compared for* **a)** *each of 11 different categories of impact and for* **b)** *each of three different damage categories. The largest effect score (index) for each pair was set to 100%. The method used was the Eco-indicator 99 (H) / Europe Ei 99 H/H using data for Europe.*

life cycle of a PVC window life cycle of a aluminium window

respective values of partial environmental indices for product life cycle phases obtained after normalisation and weighting. The index adds up to 11.1 eco-points.

Figure 9.15a shows the environmental index for the PVC window, divided into lifetime stages and damage categories. The environmental index for the production phase of the PVC window is equal to 14.1 Pt. 10 Pt result from resource depletion, which means that main environmental load is located in the "resources" damage category. On the other hand, the PVC window utilisation phase is environmentally sound (environmental index equal to –5.65), which is due to recycling of PVC, metals and glass.

As a last step of the LCA of the PVC window, let us examine the partial environmental indices for the impact categories which provide more detailed information about the processes in the product life cycle (Figure 9.15b). As has been demonstrated before, the biggest environmental load associated with the PVC window is allocated to the *resources* and *human health* damage categories. Figure 9.15b shows that for damage category *resources* the biggest contribution comes from the *fossil fuels* impact category. This is due to the combustion of crude oil and natural gas used in PVC production and energy generation.

A comparison of Figures 9.15a and 9.15b shows that emissions of *respiratory inorganic* compounds place the biggest input in the damage category *human health* (dark brown colour in Figure 9.15a). This is caused by emissions of sulphur dioxide and nitric oxides during the production of PVC profiles and steel for ferrules.

9.4 Comparing Life Cycle Assessments of PVC and Aluminium Windows

9.4.1 Objective

Two environmental impacts of the life cycles of the PVC and aluminium windows were compared in a so-called comparative LCA analysis. The analysis was carried out using the same methods as used for the individual windows. As mentioned already, the lifetime of the PVC window was assumed to be 40 years and that of the aluminium window 50 years. Thus one aluminium window has to be compared to 1.25 PVC window. Selected results of the analysis are described below.

9.4.2 Characterization

Figure 9.16a shows the outcome of the characterisation phase in the comparative analysis of the windows. According to the standard for reporting this kind of analyses, the predominant effect for each impact category is set as the point of reference and is assumed to be equal to 100%. Figure 9.16a shows that an aluminium window has a bigger environmental impact in each impact category. This is mostly due to the energy intensive process of extrusion of aluminium profiles. However, for the categories *radiation* and *consumption of minerals* the environmental impacts of both products are comparable. For the impact category *radiation*, the major contribution is caused by manufacturing of steel for ferrules, glass and EPDM rubber. The small difference between environmental impacts in this category results mainly from the longer life cycle of the aluminium window.

For the impact category *minerals consumption* both windows cause almost the same environmental impact (99.6 and 100 respectively, Figure 9.16a). In this category, however, the aluminium consumption in manufacturing of a window is not taken into account since aluminium is almost 100% recycled, and can be used in another production process without causing any environmental impact. In consequence the main contribution in this category is allocated to steel production for ferrules and anchors, which is the same for both aluminium and plastic windows.

Figure 9.16b shows the results of characterisation of the PVC and aluminium windows life cycles for damage categories. After aggregation of all impact categories into the three damage categories, the conclusions are similar in terms of impact categories, i.e. the PVC window has a better environmental profile. After this step of comparative analysis there is no doubt that the PVC window is, environmentally speaking, the better product.

9.4.3 Normalisation

Figure 9.17a shows the results of normalisation carried out using the Eco-indicator 99 method. Here we see the proportions between environmental impacts produced by the two windows during their life cycles. The normalisation step did not change any conclusions about the superiority of the PVC over the aluminium window in terms of environmental impact.

9.4.4 Weighting

The results of weighting carried out by the Eco-indicator 99 method is reported in Figure 9.17b. Despite the preferences set to ecosystem quality (weighting factor 400), human health and resources (300), *resource* depletion resulting from the production phase of the windows causes the dominating environmental effects.

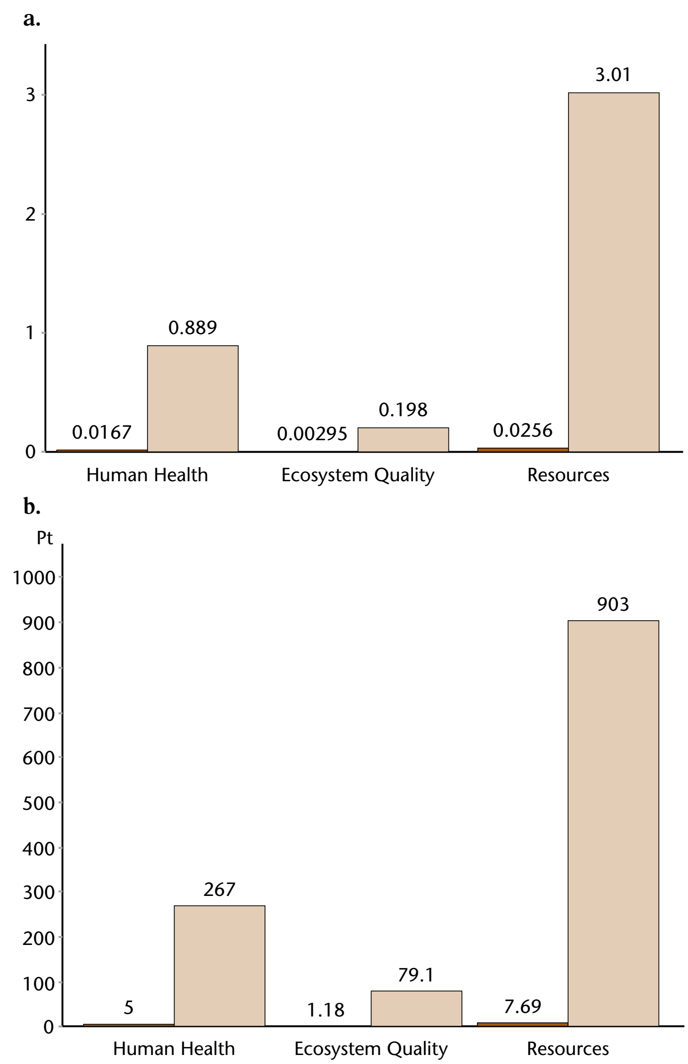


Figure 9.17 Comparative analysis of the Aluminium and PVC frame windows – normalisation and weighting for each of three different damage categories. a. *Normalised scores for the LCA of the two windows.* **b.** *The normalised and weighted scores for the two windows. The method used was the Eco-indicator 99 (H) / Europe Ei 99 H/H using data for Europe.*

life cycle of a PVC window — life cycle of a aluminium window

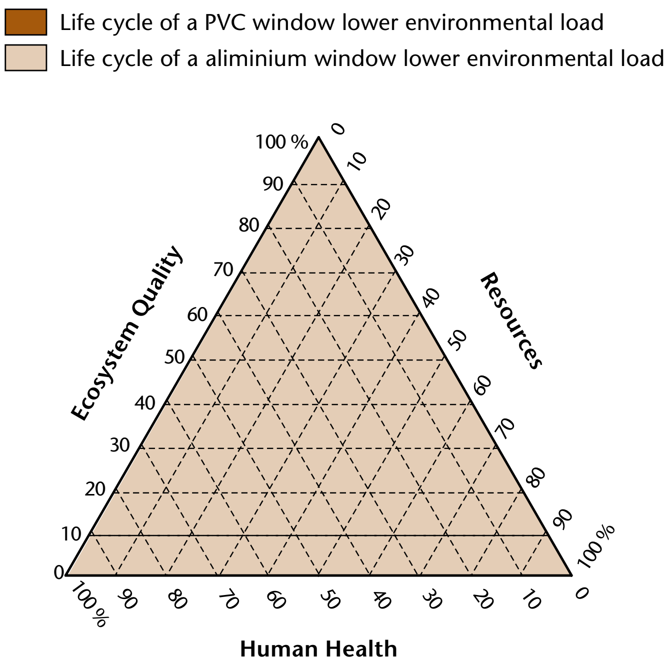


Figure 9.18 Weighting triangle of the comparison of the LCA of Aluminium and PVC frame windows. *The triangle shows how the weighting factors selected for the three impact categories influences the results. Here it is clear that the aluminium frame window contributes more than 99% of the environmental load of the two windows regardless of choice of weighting factors (compare for example Figures 6.8 and 6.9).*

The weighting phase in any LCA remains the most doubtful and controversial analysis because of the subjective assessment of environmental issues. One of the possibilities of illustrating the results of the weighting phase, if three damage categories are distinguished, is to use a *weighting triangle* [Goedkoop and Oele, 2001]. A weighting triangle indicates to what extent the result of an analysis is dependent on weighting factors.

The comparative analysis of the windows life cycles carried out with the aid of the weighting triangle shows that the results of the weighting phase are independent of the applied set of weighting factors, and that the plastic window is always superior over the aluminium window in environmental terms (Figure 9.18). The whole area of the weighting triangle is light brown which indicates that the life cycle of PVC window causes a lower environmental load for the whole range of weighting factors (i.e. for priority levels from 0-100%), for each damage category.

9.4.5 Process Contribution Analysis

Process contribution analysis is used to determine which processes in the life cycle of a product are most important, and to calculate their respective contributions in the environmental index. This information allows us to significantly simplify a process tree and focus our attention on the most important components and processes in the life cycle.

A process contribution analysis for the life cycles of both windows is given in Table 9.10. The table lists the contributions in percent of each process to the overall environmental index of the windows. For the aluminium window the extrusion and extraction of crude oil (50%) and other use of fossils definitely dominate the environmental profile. In the life cycle of the

Table 9.10. Process contribution analysis for the Aluminium and PVC frame windows. *Selected relative contributions (percentage) to environmental load of major processes in the life cycles of the two windows as calculated by the SimaPro software.*

Process	Unit	ALU window
Total of all processes	%	100
Remaining processes	%	0,9532
Crude oil I	%	50,29
Extruding alum I	%	13,28
Natural gas I	%	11,63
Electricity UCPTE oil I	%	11,07
Electricity UCPTE coal I	%	6,519
Electricity UCPTE nuclear I	%	3,475
Natural gas B	%	1,458
Aluminium ingots I	%	0,857
Powerplant lignite I	%	0,684
Steel high alloy ETH T	%	0,5459
Powerplant gas I	%	0,2599
Bauxite	%	-0,3014
Aluminium raw bj	%	-0,3546
Glass (white) B250	%	-0,3628

Process	Unit	PVC window
Total of all processes	%	100
Remaining processes	%	4,409
PVC suspension A	%	62,03
Steel high alloy ETH T	%	41,64
Electricity UCPTE Med. Voltag	%	24,89
Float glass uncoated ETH T	%	15,88
Extrusion PVC I	%	6,885
Recycling ECCS steel B250	%	5,677
Heat diesel B250	%	5,285
EPDM rubber ETH T	%	4,153
Electricity UCPTE gas I	%	4,136
Steel I	%	2,105
Bulk carrier I	%	2,048
Glass 100% recycled B	%	-3,012
ECCS steel sheet	%	-9,875
PVC P	%	-66,25

PVC window, however, no such single process dominates. The production of PVC suspensions contributes about 62% to the environmental index, the production of steel high alloy about 42%. PVC recycling reduces the index about 66%.

9.4.6 Single Score

The final step of the comparative LCA is a determination and comparison of single scores for both windows. In Figure 9.19 the environmental index for the PVC window is equal to 0,0139 kPt (thousands of eco-points), while for the aluminium window 1.25 kPt (thousands of eco-points). The ratio of environmental indices is approximately 1:90.

Thus a comparison of the environmental indices for the life cycles shows that the production, usage, and disposal phases of the aluminium window cause about *90 times* greater environmental load than the same phases of a PVC window.

9.4.7 Sensitivity Analysis

From the point of view of environmental protection, selecting PVC windows for both household and industry is recommended. However, uncertainties associated with data accessibility, reliability and relevance and the lack of an accepted methodology for LCA analysis makes the final outcome to be only qualitative. To examine how sensitive the results of LCA analysis might be to data quality and assumptions in the life cycle model, a *sensitivity analysis* was performed. Changes in the final score as a function of different technology applied in the production phase, the different lifetime, and different disposal scenarios were analysed.

9.4.8 The Influence of the Technology

In the life cycle of the aluminium window we have to assume which technology was used to produce the aluminium profiles. The technology selected from the SimaPro database and used in life cycle modelling refers to the production of aluminium parts of windows and cars. In the database it is called *extruding aluminium*. However, it is not known which technology was applied to extrude the profiles of the window analysed (this information was not available during the inventory analysis). In the SimaPro database there are two other technologies for aluminium extrusion:

- Aluminium extrusion – this technology does not encompass aluminium production
- Alu tubes production – technology of the extrusion of aluminium tubes annealed at temperature 450 °C and coated inside and outside.

To investigate the influence of the production process we conducted a sensitivity analysis of the aluminium windows, in which the process of *extruding aluminium* was replaced by the processes of *aluminium extrusion* and *alu tubes production* in the production phase (Figure 9.20a). The effect of the analysis shows a dramatic decrease in the ratio of the indicators from 1:90 to 1:1.36 for *aluminium extrusion* technology and to 1:1.25 for *alu tubes production*. The sensitivity analysis shows that irrespective of which data we use the lower environmental index is ascribed to the plastic window, albeit 36 or 25% rather than 90 times. The sensitivity analysis shows the selection of the technology for aluminium profiles production is decisive for the environmental impact of the whole life cycle of an aluminium window.

9.4.9 Different Lifetime

Plastic and aluminium windows were designed to be in operation for a relatively long time, so we cannot determine precisely the length of the products' life cycle neither its disposal scenario. For the LCA analysis presented here, the estimated lifetime is 50 years for an aluminium window and 40 years for a plastic window.

To check if lifetime of the products influences the environmental profile of the windows, a comparative LCA was performed for shorter (30 years) and longer lifetime periods (60 years) for both products (Figure 9.20b). The functional unit

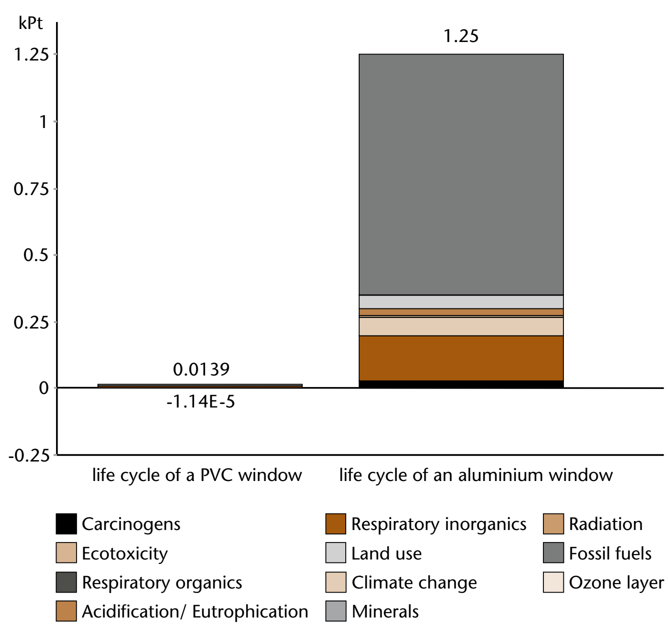


Figure 9.19 Final environmental scores (index) for the life cycles of the Aluminium and PVC frame windows. *The scores are shown for each of 11 different impact categories. Numerical values are in thousand eco-points (kPt). The method used was the Eco-indicator 99 (H) / Europe Ei 99 H/H using data for Europe.*

remains the same (a 50-year lifetime is the point of reference, see above).

As we could expect, the longer the lifetime of the product, the better the environmental profile. The environmental index for aluminium window dropped from 1.25 for a lifetime of 50 years to 1.04 for a lifetime of 60 years and went up to 2.08 for a lifetime of 30 years.

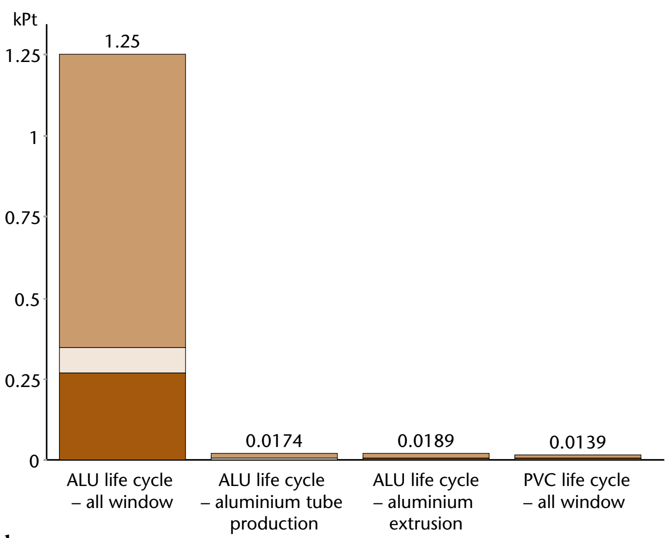
However, this aspect of a life cycle hardly influences the results of a comparative analysis. A plastic window used for 30 years (environmental index 0.0183) is still much more environmentally friendly than an aluminium window used for 60 years (environmental index 1.04). The ratio of environmental indexes is now approximately 1:55.

9.4.10 Different Disposal Scenarios

Above we assumed a similar disposal scenario for both windows: plastic and aluminium elements, supports, handles, ferrules, anchors and panes are recycled, gaskets are discarded, partly incinerated and partly land filled, based on a Dutch scenario of municipal waste utilisation.

Different disposal scenarios did not significantly affect the environmental profiles of the windows (Figure 9.20c). The environmental index of the aluminium window did not change (~1.25), while for PVC windows it increased slightly from 0.0139 to 0.022, when recycling was reduced and land filling and incineration were increased. The result was expected as the production phase generates the strongest impact on the environmental index of both windows.

a.



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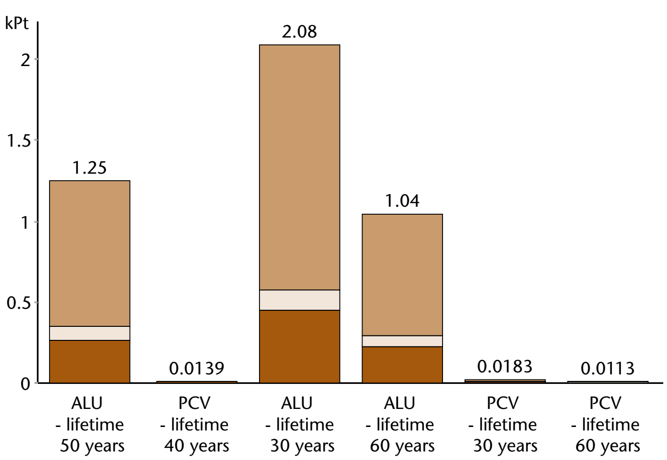

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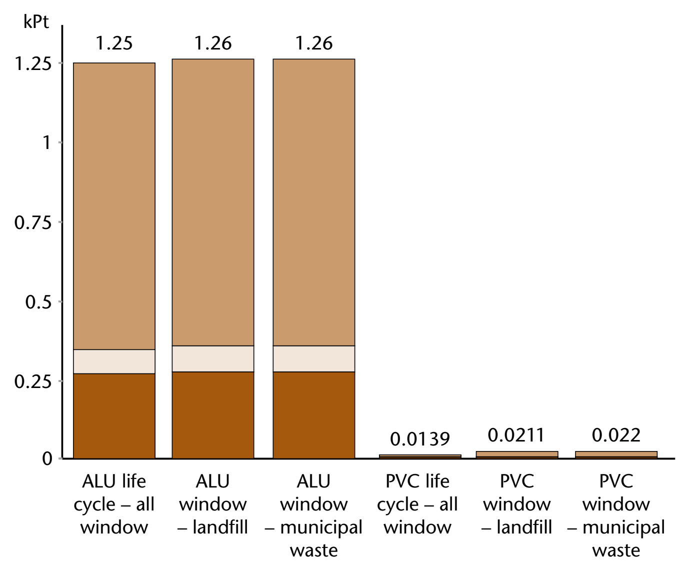

Figure 9.20 Sensitivity analysis of the LCA analysis of the Aluminium and PVC frame windows for production method, life time and wasting method divided between three damage categories. a. *Influence of the production process showing (from left to right) basic scenario, aluminium tube production, and aluminium extrusion. The environmental load of the PVC frame window production is shown for comparison.* **b.** *Influence of life time showing (from left to right) basic scenario, life times of 30 years and life times of 60 years.* **c.** *Influence of method for wasting showing (from left to right) basic scenario, land-filling, and municipal waste treatment with incineration. Numerical values are thousand of eco-points (kPt).*

Human Health Ecosystem Quality Resources

Student Exercise

All steps in “Windows” project described in the book can be analysed during classes with students. With this aim complete the following procedure:

Download a demo version of SimaPro directly from the EMS CD attached to the book or alternatively at: http://www.pre.nl/simapro/default.htm

You can start Install Shield Wizard at EMS CD\SP-5Demo\Disk1\Setup.exe. You will be asked where you want to install you SimaPro demo. Advisably accept default location at C:\ProgramFiles\SimaPro 5 Demo. If you prefer to install it somewhere else please remember the location. Now you can start SimaPro from the desktop (while initialisind choose single-user analyst version). You are encouraged to run the Guided Tour, which is a comparative analysis of different models of coffee machine and is a standard SimaPro case study. Its aim is to get you accquainted with the most important features of the software.

SimaPro 5 demo gives you the access to 8 database libraries (BUWAL 250, Data Archive, Dutch Input Output Database 95, ETH-ESU 96 System processes, ETH-ESU 96 Unit processes, IDEMAT 2001, Industry data, methods) and 2 case studies (Guided Tour, Tutorial with wood example). Demo version allows you to analysed already conducted projects. You are not permitted, however, to make any changes.

To get the access to “Windows” project you have to replace your database which can be found in SimaPro program files (C:\Program Files\SimaPro 5\Database, unless you installed it somewhere else) by the database provided on the CD. Please, follow the instruction:

1. Open SimaPro files on your computer (C:\Program Files\SimaPro 5\Database, unless you installed it somewhere else) and delete the whole folder “Database”.
2. Copy whole folder “Database” from the EMS CD and paste it at C:\ Program Files\SimaPro 5.
3. Open the new database you have just pasted and select all files.
4. Click once with the right button and select “properties” item. Untick “read only” checkbox.
5. Close the database and start SimaPro from the desktop.

Now, go ahead and run your classes on LCA on “Windows”.

Study Questions

1. Which part of the ALU frame window life cycle has largest environmental impact, and how can it be changed to reduce the impact.
2. Which part of the PVC frame window life cycle has largest environmental impact, and how can it be changed to reduce the impact.
3. List the parts of the life cycles of the two windows which have a negative environmental score (reducing environmental impact). What exactly do they consist of?
4. Describe how you go from inventory to characterisation to normalisation to weighting for a particular component in the process tree.
5. Explain the final environmental index, expressed in so-called eco-points in the eco-indicator 99 method.
6. The comparative LCA analysis of the two windows can be interrupted at each level in the sequence (characterisation, normalisation, weighting). Describe and give interpretation of differences in LCA score after each of these steps.

Abbreviations

ALU	Aluminum.
DALY	Disability Adjusted Life Years.
EPDM	Ethylene Propylene Diene Monomer (rubber).
PDF	Potentially Disappeared Fraction.
Pt	Eco-points.
PVC	Polyvinyl Chloride.
VOC	Volatile Organic Compounds.

Internet Resources

PRé Consultants: Eco-indicator 99
impact assessment & ecodesign method
http://www.pre.nl/eco-indicator99/

PRé Consultants: SimaPro 6 LCA software
http://www.pre.nl/simapro/default.htm

Aluminium production technology:
European Aluminium Association
http://www.azom.com/details.asp?ArticleID=1554

Polyvinyl Chloride production sustainability:
INEOS Vinyls Company
http://www.evc-int.com/she/waste.htm#pvcproducts

Polyvinyl Chloride production technology:
INEOS Vinyls Company
http://www.evc-int.com/worldofpvc/manufact.htm