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Environmental performance of lead sheet and alternative weather-proofing products

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Summary

Based upon the life cycle assessment of lead sheet and other weather-proofing products the following conclusion is drawn:

CONCLUSION

Lead sheet has the best environmental performance as a weather-proofing product of all the products that were assessed. For cavity wall applications the alternative products were aluminium-reinforced SEBS, reinforced EPDM and plasticised PVC sheet, while for wall-roof junctions the alternatives were aluminium-reinforced SEBS and aluminium-reinforced PiB sheet. For use as a valley gutter, lead sheet was compared with glass-reinforced polyester.

The functional unit used as the basis of the comparison was 1 m^2 installed weather-proofing material for a 75-year service period in the Netherlands and Germany. This functional unit was applied for all three functions (cavity wall, wall-roof junctions and valley gutter) analysed in the study.

In Figure S1 the results of the comparison are shown graphically with the net environmental impact of each product expressed as a “shadow cost”. This approach of summing the costs associated with the required abatement of the diverse environmental effects enables a simple comparison to be made between different products.

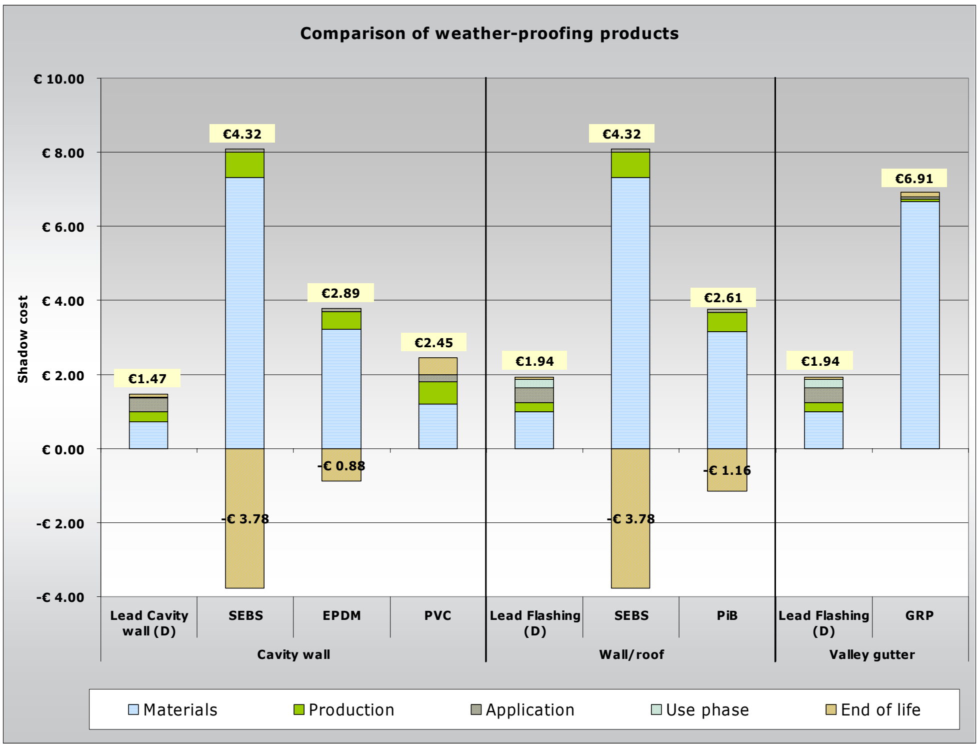

Figure S1 Comparison of the environmental performance expressed as shadow cost (€) of products for weather-proofing of cavity walls, wall-roof junctions and as valley gutters. The value in the box on top of each bar gives the total net shadow cost of each product. For lead sheet applications the German (D) situation has been used.

The good environmental performance of lead sheet compared with the other products is largely due to its long service life and its limited need for primary raw materials. The largest part of the environmental impact of lead sheet results from small losses of lead during installation and end of life collection which cause the life cycle not to be fully closed. From a life cycle assessment perspective, such losses are expected to be replenished with primary lead. However the modelling of the losses in this way is a very conservative approach because in reality the losses would be made up from secondary lead which is available in abundance as a result of extraordinarily high levels of lead recycling.

An issue that is generally regarded as important is the run-off of lead compounds from the corrosion of lead sheet which is exposed to the environment. Part of the corroded lead is emitted to the environment (soil and surface water), but another part forms a patina on the lead sheet or is adsorbed onto the building. Recent data on the run-off rate (0.88 $g.m^{-2}.y^{-1}$) have been used.

Sensitivity analyses for the SEBS:bitumen ratio for the aluminium reinforced SEBS-bitumen, for the production process of the glass fibre reinforced polyester and for the recovery percentage of aluminium from the aluminium reinforced products showed some impact on the environmental performance of the products but did not result in a change in the ranking of the products.

Life cycle assessment methodology

In this study an improved life cycle impact assessment methodology has been used which is based on the widely-used CML2 method. In recent years it has become clear that the toxicity-related impact of some substances, and especially of metals, was inadequately addressed in the CML2 method. As a result this problem was addressed by a group of specialists in the 'Declaration of Apeldoorn'. One of the points to be improved is to base the toxicity impact of a substance on its HC50[1] rather than on its PNEC[2] as is done in the CML2 method. A full adaptation of the CML2 method in this respect was far beyond the scope of this study. However, the improvement was made for the ten substances that contributed most significantly to the toxicity impact of all the products being assessed.

The environmental impact of the products is based on this improved CML2 method and is expressed as a monetary value. This value is obtained by multiplying the result of the impact category (global warming potential, ecotoxicity potential, etc) by the price of emission abatement for the category in question. The use of these so-called "shadow prices" is seen as a robust and realistic method of translating the results of the ten baseline impact categories into a single value. Shadow prices allow a much easier comparison of alternatives than showing environmental profiles made up of the ten individual impact categories in the CML2 method.

Report layout

The goal and scope for comparing the weather-proofing products is described in Chapter 2, while the products are described in detail in Chapter 3. This includes the mass per functional unit, transport needs and the treatment of waste occurring during the production, installation and at the end-of-life of the products. The improved life cycle impact assessment method is described in Chapter 4 followed by the actual impact assessment and comparison of products in Chapter 5. To determine the impact of uncertainties concerning the main assumptions a number of sensitivity analyses were made. The results of these are found in Chapter 6. Finally, the conclusions of the study are drawn in Chapter 7.

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[1] HC50 is the Hazardous Concentration at 50% calculated as the geometric mean of the LC50 (lethal concentration for 50% of the individuals) or EC50 (environmental effect concentration).

[2] PNEC stands for Predicted No Effect Concentration.

Table of contents

1. Introduction

ELSIA, the European Lead Sheet Industry Association, is concerned about the suggested environmental burden in relation to the use of lead sheet in the building process. TNO has conducted a number of studies on this topic, ranging from a full life cycle assessment (LCA) to a run-off analysis. One of these studies, published in 1998, was a comparative LCA called “Environmental and costs comparison of lead sheet and two alternative materials” [1].

ELSIA has requested TNO to update the LCA part of the 1998 report, based on the currently available data for the materials to be compared. The updated study should also address the recently improved insights into the ecotoxicity of lead and other metals.

The study is primarily intended for the lead sheet industry to provide them with a better insight in the environmental performance of lead sheet compared to alternative products based on PiB, SEBS modified bitumen, PVC, polyester and EPDM. The report is also aimed at informing actors in the building process in the widest sense like authorities, consultants and architects.

2. Goal and scope

2.1 Introduction

The LCA study will be executed following the ISO 14040ff standards for life cycle assessment. ELSIA made efforts to involve the producers of the alternative materials into this LCA but did not succeed in this. Therefore, this study will deviate from the ISO requirement that for public reports on competitive alternatives with the same function, the LCA should be reviewed by a review panel with representatives of the alternative materials.

2.2 Goal of the comparative LCA

The goal of the study is to draw up a comparison of the environmental impact of the use of lead sheet as building weather-proofing produced by the European producers with the environmental impact of selected competing materials applied at the German and Dutch markets. The study will enable ELSIA to compare the environmental impact of lead sheet with that of the competing materials and see what issues relate to the life cycle of lead sheet and other materials applied as weather-proofing materials.

Weather-proofing a building can be divided in a number of different functions. Lead sheet can be used as roof or wall cladding, protecting cavity walls and protecting the transition from roof to wall. The three functions investigated here, are:

- Weather-proofing material used in cavity walls (lead sheet, aluminium-reinforced SEBS, reinforced EPDM, PVC);
- Weather-proofing material in wall-roof junctions (lead sheet, aluminium-reinforced SEBS, aluminium-reinforced PiB);
- Discharge of rainwater by valley gutters from sloping roofs (lead sheet, glass-reinforced plastic).

Cavity wall applications are mainly used for walls made out of porous stone as this type of material may lead to water being transported through the brickwork. This application is most commonly used in the Netherlands.
With respect to the wall-roof applications, the present study will focus on applications in non-porous stone. In the case of porous stone, the cover flashing must be cemented further into the stone leading to less of the total material used exposed to the environment. In the case of non-porous stone, there will be sufficient water sealing when the flashing is cemented just slightly into the stone.

2.3 Target group

The target group can be defined as the members of ELSIA and third parties engaged in weather-proofing applications. This involves actors in the building industry, such as architects, building contractors, maintenance companies, authorities etc.

2.4 Functional unit

The functional unit defines the quantification of the identified weather-proofing functions. One of the primary purposes of a functional unit is to provide a reference to which the input and output data are related to [1].
In the study, we took the functional unit to be:

The use of 1 m^2 installed weather-proofing material for a 75-year period in the Netherlands and Germany.

This functional unit is applied for all the functions (cavity wall, wall-roof application and valley gutter) analysed in this study.

The installed material is for all functions partly covered by the brickwork or roof cladding (valley gutter) and partly exposed to the elements.

The inventory of processes and materials needed to fulfil the functional unit will be given in section 3.2.

2.5 System boundaries

The product systems are studied from the cradle (extraction of raw materials) to the grave (treatment after service life). The following activities are included:

1. inputs and outputs in the main manufacturing/processing sequence;
2. distribution/transportation;
3. production and use of fuels, electricity and heat;
4. use and maintenance of products;
5. disposal of process wastes and products;
6. recovery of used products (including reuse, recycling and energy recovery).

2.6 Data quality

Descriptions of data quality are important to understand the reliability of the study results and properly interpret the outcome of the study. The data quality requirements in this study include the following parameters:

- Time-related coverage: the data should relate to recent (2000-2005) process data;
- Geographical coverage: data should be valid for processes applied in Germany and the Netherlands. In case this information is lacking data for Western-Europe shall be used;
- Technology coverage: the technology should be based on the actual process mix or a representative process.

2.7 Allocation

Industrial processes may produce more than a single product. In other words they are multifunctional. In these cases an allocation step is necessary: all input and output data of the unit process are allocated to each of the products, according to chosen rule (e.g. on basis of mass ratio or economic value).

For lead sheet the allocation of the recycling is approached as a closed-loop situation. This means that lead sheet is recycled to primarily produce new lead sheet.

3. Inventory

3.1 Introduction

In the life cycle inventory (LCI) phase of executing an LCA the product systems are defined in terms of life cycle stages included/excluded. Furthermore the ‘recipes’ to fulfil the functional unit are compiled and described in terms of material and energy use and the emissions of substances to the environment and the generation of waste.

The product systems include the following stages:
1. Production of raw materials
2. Production of the cavity wall sheets, flashing sheets and valley gutter sheets
3. Application at the building
4. Use of cavity wall sheets, flashing sheets and valley gutter sheets
5. Demolition and end-of-life.

These stages will be discussed for each material in the following sections of this chapter. Issues that are common to all materials are discussed separately.
Detailed information on the LCI data used to calculate the environmental impacts is given in Appendix C.

3.2 General inventory data

Application
No effects of the application itself (i.e. use of tools, transport on building site, et cetera) have been accounted for.

Application losses
When the materials are being installed material is lost due to cutting the material at the right size. For all materials the amount lost at installation is estimated to be 5%.

Collection of application losses
It has been assumed that all application losses go to the end-of-life waste treatment. The only exception to this is lead sheet. Due to its high economic value 100% of the losses are collected and send to a lead recycler.

Collection at end-of-life
Due to Dutch and German policies to collect demolition waste for recycling or for recovery most of this waste is recovered or recycled. Based on average Dutch [6] and German [5] figures the amount that is collected for this purpose is on average 88%. It has been assumed that for all materials, except lead sheet, recovery is the end-of-life option. Recovery is assumed to be in the form of energy recovery taking

place in a municipal solid waste incinerator (MSWI). Aluminium mesh present in some materials is recovered from the bottom ashes and sent to a recycler.

Of the remaining 12% of material not collected for recovery, 98% goes to a landfill and 2% to an MSWI (see also Table 1).

Table 1 Recovery/recycling and waste treatment percentages.

Destination	Division	Sub-division
Waste recovery	88%	
Treatment non-recovered waste	12%	
- MSWI		2%
- Landfill		98%

Lead sheet is an exception as 97.5% of the material is collected for recycling. This high collection rate is due to the high economic value of used lead sheet. The remaining 2.5% follows the same route as the non-recovered waste stream for the other materials.

Removal during service life and at the end-of-life of the building

Products with a lifespan shorter than that of the building (75 y) are removed and re-installed after their service life ends. The impacts of the removal and reinstallation processes have not been included in the LCA as it is expected that these effects are insignificant.

Transport

Transportation occurs at many instances of the product chain. It starts with the transports from the raw material producer to the producer of the water proofing sheets and ends with the transport from the site of demolition to the waste treatment.

A number of transport distances have been assigned common values. These are shown in Table 2.

Table 2 Common transport distances used in the study.

Transport	Material	Distance
Raw materials to sheet producer	Aluminium and lead (Germany)	250 km
	Bitumen, plastics, elastomers, minerals and lead (Netherlands)	100 km, return empty
Sheet producer to building site	PiB, SEBS modified bitumen, EPDM, PVC and GRP	250 km
	Lead (Germany)	250 km, return empty
	Lead (Netherlands)	150 km, return empty
Building site to waste treatment	All materials to recycler	100 km
	All materials to MSWI	150 km, return empty
	All materials to landfill	100 km, return empty

The transports from raw material producer to sheet producer will in general be without the intermediate step of wholesalers. Transport from the sheet producer to the building site may use wholesalers as an intermediate; this has been included in the estimated distance. The transport from the building/demolition site to the waste treatment is based on a trip of 50 km to a sorting installation and added distances to the recycler, MSWI and landfill.

3.3 Lead sheet

3.3.1 Production of raw materials

For the production of lead sheet recycled lead is exclusively used as a raw material. The lead scrap is melted and refined by removing unwanted elements and by adding small amounts of alloying copper; an amount of 0.05% copper is used in this study, to give the lead its desired properties. The molten lead is cast into ingots.

The melting and refining processes yield secondary lead (93.4% mass) and give by-products in the form of lead drosses and other metals drosses. These drosses are sold on the market. To allocate the environmental impacts of the melting and refining to these by-products the economic value has been used. Lead drosses then account for 1.7% of the impacts, while the other metal drosses account for 0.6%.

As the product cycle of lead sheet used in buildings is not 100% closed, 2.5% of the lead is not recovered from the building and a small part of the lead is lost due to corrosion, this lost part of the secondary lead has to be replenished. Although lead sheet is made from secondary lead the loss of lead from the product cycle leads to a certain need for primary lead within the total product system of lead. One could thus argue that the amount of lost lead must be accounted for by using the environmental impact of primary lead. This would lead to an overestimation of the impact as the lead sheet system only uses recycled lead. By using the method of value-corrected-substitution [7] only part of the impact of primary lead is allocated to the lead sheet product system. The amount is based on the ratio between the price of primary lead and that of secondary lead. Given the current average prices of €1100/ton and €850/ton for primary and secondary lead this ratio becomes 0.773. So only 77.3% of the amount of primary lead needed for replenishing the market is accounted for. This approach to account for the losses of lead from the lead sheet life cycle is seen as a conservative approach.

The average distance from the recycler to the lead sheet producer amounts to 100 km in the Netherlands and 250 km in Germany.

3.3.2 Production of the cavity wall sheets and flashing sheets

After the ingots have cooled down sufficiently they are rolled to form sheets. For the application as weather-proofing material a weight of 18 kg per m^2 is used. This gives a thickness of 1.59 mm.

Characteristics of the lead sheet [1] are:

– thickness	1.59 mm
– weight	18 kg.m^{-2}
– width	10 – 50 cm
– length	300 cm

Figure 1 Lead flashing used at a wall-roof transition [4].

3.3.3 Application at the building

Lead sheet is used in two applications; in cavity walls for porous stones and for wall/roof junctions in non-porous stones (see for the latter Figure 1).
Due to cutting losses et cetera the losses at application are 5%, which means that 18.9 kg is needed to apply 1 m^2 of lead sheet. These losses of 0.9 kg lead are taken back by the builders and sent back to a lead recycler.

The average distance from lead sheet producer to building site amounts to 150 km in the Netherlands and 250 km in Germany. The average distance from building site to recycler amounts to 100 km, both in the Netherlands and Germany.

The lead sheet is produced and applied conform The European CEN-EN 12588 standard.

3.3.4 Use of cavity wall sheets and flashing sheets

In this stage lead sheets have a lifespan comparable with that of the building which is 75 years. During use the surface of lead sheet gradually builds up a strong and practically insoluble oxidation layer, which then impedes corrosion. This leads to a commonly reported run-off rate (see e.g. [8]) of 5 $g.m^{-2}.y^{-1}$. For flashings a lower run-off rate of 0.88 $g.m^{-2}.y^{-1}$ is appropriate [8]. Recent Dutch studies have shown that this run-off rate is an overestimation. A study by RIZA showed that the current run-off rate of 5 $g.m^{-2}.y^{-1}$ assumed for lead sheet in the Dutch emission inventory is too high; a value of 2.8 $g.m^{-2}.y^{-1}$ is advised as a new value [9]. A more recent study showed that this value is even likely to be too high. Hulskotte [12] estimated that a run-off rate of 1.14 $g.m^{-2}.y^{-1}$ would be the best estimate for the Dutch situation. Data from a study by TNO for lead sheet applied as flashings at artificial roofs [10] showed that the run-off rate measured over a two year period is 0.89 $g.m^{-2}.y^{-1}$, this is close to the value for the run-off in the risk assessment report [8]. In the same TNO study the corrosion rate, measured at an isolated lead sheet, was estimated at 4.4 $g.m^{-2}.y^{-1}$.

In this discussion it is important to know that the corrosion rate and the run-off rate are in fact two different parameters. In practice these two terms are not always separated and sometimes used incorrectly. The corrosion rate is the amount of material that is lost due to corrosion; this parameter is needed to calculate how much material is left after a certain period. The run-off rate is what leaves the building and enters the environment. Part of the corrosion products are, as a matter of fact, retained by the surface over which the water flows.

In this study we will use as the corrosion rate a value of 4.4 $g.m^{-2}.y^{-1}$ [10]. For the run-off rate a value of 0.88 $g.m^{-2}.y^{-1}$ [8] will be used.

As corrosion only takes place where the lead sheet is exposed to the atmosphere the size of the exposed surfaces is of importance. These surfaces are:

- cavity wall sheet 10%
- flashing sheet 95%

Run-off model

The lead corrosion products that enter the drainage system (gutters, downpipes) of the building are mainly (90%) discharged into the sewer system (see Figure 2). For the buildings of which the drainage system is not connected to the sewer system part of the run-off is discharged directly onto or into the soil (6.5%) or to the surface waters (3.5). The run-off model for a Western European situation is an update of a former model [1] and describes the situation of 2001-2002 [13].

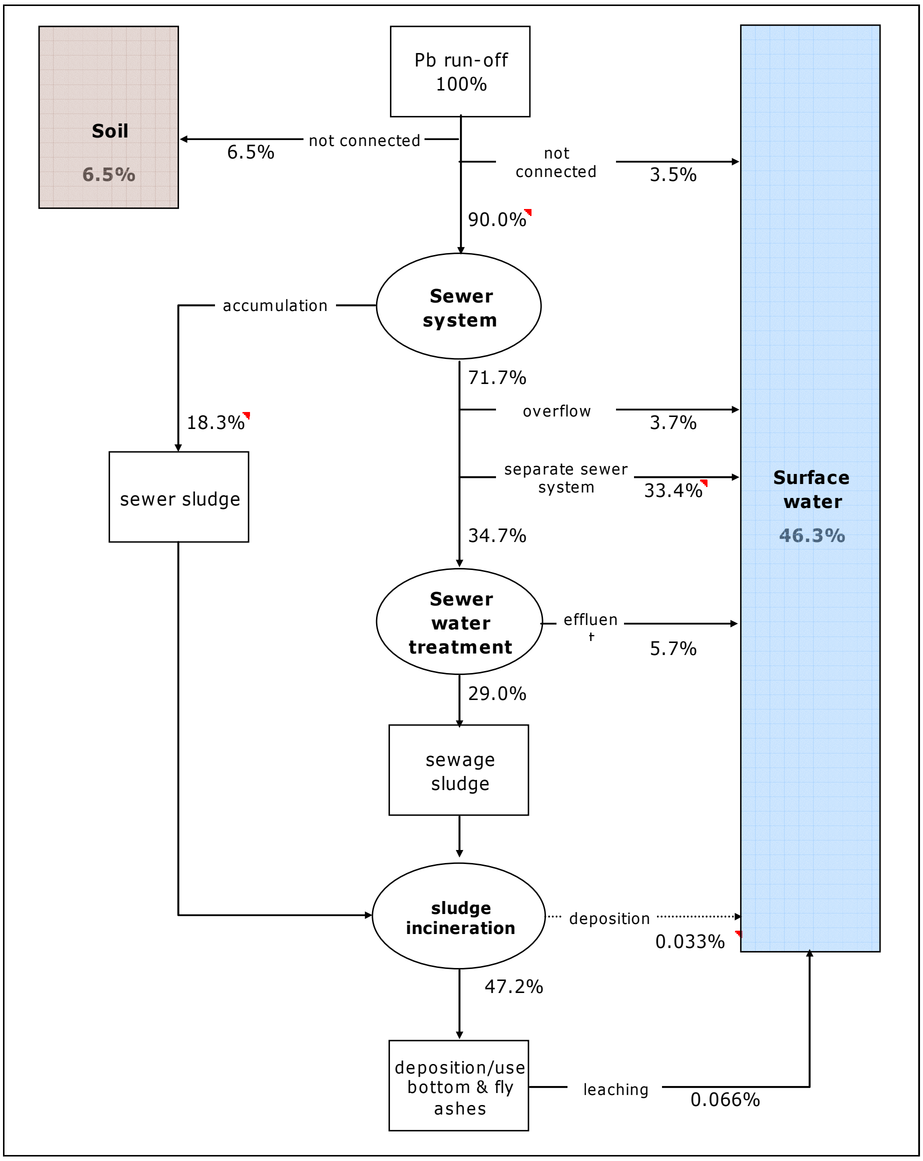

Figure 2 Distribution model for lead emissions from buildings for a Western European situation.

3.3.5 Demolition and end-of-life

After 75 years the building is demolished and all lead sheets are removed. It has been estimated that 97.5% of the removed lead waste is recycled, while the remainder is sent to waste treatment.

3.3.6 Flow chart and transport needs

From the preceding sections describing the life cycle of lead sheet two flow charts have been distilled. The first one (Figure 3) describes the use of lead sheet in cavity walls; the second (Figure 4) that of lead sheet used in wall/roof junctions. The two differ in the amount of lead corroded due to differences in exposed surface.

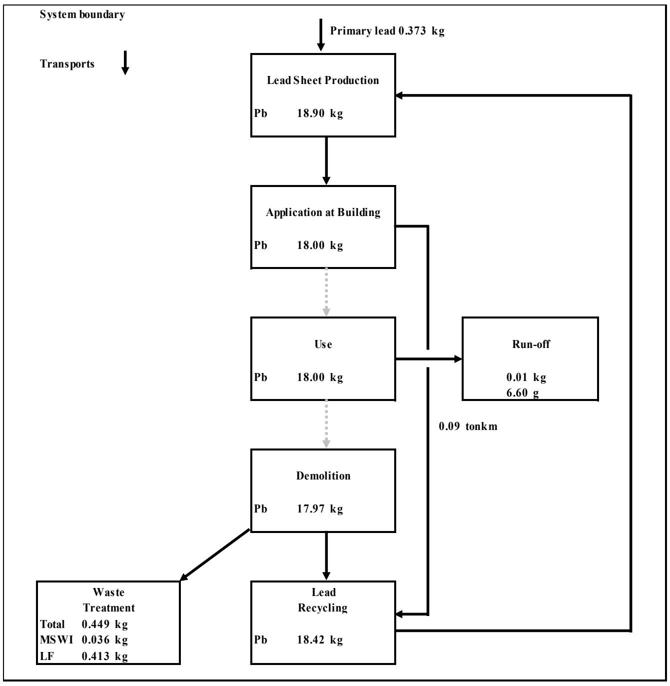

Figure 3 Flow diagram life cycle of lead cavity wall sheet (Dutch situation).

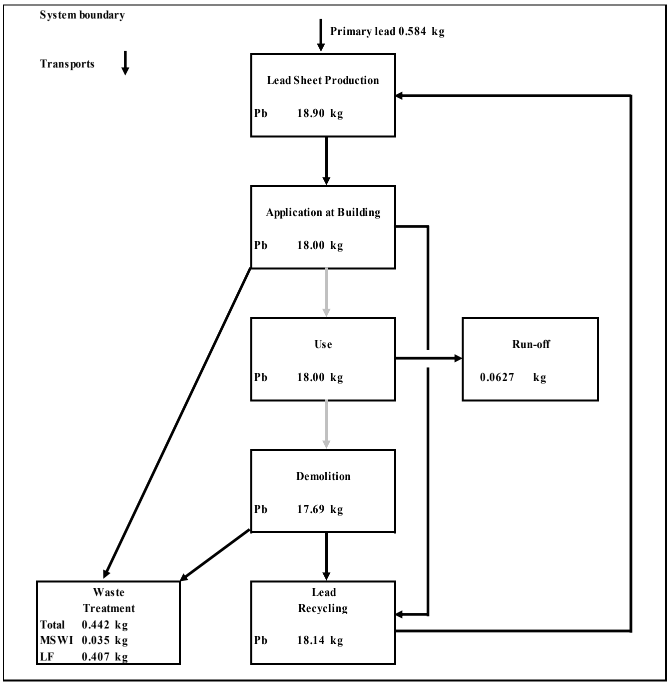

Figure 4 Flow diagram life cycle of lead flashing sheet in wall/roof junctions (Dutch situation).

Two cases considering the transport distances have been chosen. The first one describes the Dutch situation, the second one the situation for Germany. The transport data consider the need for transportation with respect to production, use and discard of lead sheet used as cavity wall sheet and flashing sheet in buildings.

In Table 3 up to Table 6 the specification of the transport, the distance, the occurrence of an empty return trip ('Return') and the resulting transport need in tonkm have been given for both types of application and both countries.

Table 3 Transport data of lead sheet in cavity wall application in the Netherlands.

From	To	Distance (km)	Return	Tonkm
Lead recycler	Lead sheet producer	100		1.89
Lead sheet producer	Building site	150	x	5.40
Building site	Lead recycler	100		1.84
Building site	Waste incinerator	150	x	0.011
Building site	Landfill	100	x	0.083

Table 4 Transport data of lead and lead flashing sheet in the Netherlands.

From	To	Distance (km)	Return	Tonkm
Lead recycler	Lead sheet producer	100		1.89
Lead sheet producer	Building site	150	x	5.40
Building site	Lead recycler	100		1.81
Building site	Waste incinerator	150	x	0.011
Building site	Landfill	100	x	0.081

Table 5 Transport data of lead and lead cavity wall sheet in Germany.

From	To	Distance (km)	Return	Tonkm
Lead recycler	Lead sheet producer	250		4.73
Lead sheet producer	Building site	250	x	9.00
Building site	Lead recycler	100		1.84
Building site	Waste incinerator	150	x	0.011
Building site	Landfill	100	x	0.083

Table 6 Transport data of lead and lead flashing sheet in Germany.

From	To	Distance (km)	Return	Tonkm
Lead recycler	Lead sheet producer	250		4.73
Lead sheet producer	Building site	250	x	9.00
Building site	Lead recycler	100		1.81
Building site	Waste incinerator	150	x	0.011
Building site	Landfill	100	x	0.081

3.4 Aluminium reinforced PiB

This weather-proofing material is made out of the elastomer poly-isobutylene (PiB), an aluminium mesh and two bands of bitumen. The aluminium mesh allows bending of the material and guarantees a certain stiffness of the material. It is used for chimney flashings and beneath ridge tiles. A limitation of aluminium reinforced PiB is that it can not be used for cavity walls applications.

Wakaflex from Lafarge Roof Products is an example of flashing material made from aluminium reinforced PiB (see Figure 5).

Figure 5 Wakaflex, a aluminium reinforced PiB flashing material from Lafarge Roof Products.

3.4.1 Production of raw materials

Aluminium reinforced PiB consists of the following materials:
- PiB (polyisobutylene) bulk
- Aluminium
- Butyl adhesive

The LCI data for the production of PiB are based on the updated data from the previous study [1]. In the update recent sources for the energy consumption have been used. The amount of butyl adhesive has been assumed to be negligible (less than 2%).

3.4.2 Production of the cavity wall sheets and flashing sheets

An aluminium mesh is incorporated into plasticised PiB. The mass ratio between PiB and aluminium is 84:16 [1]. No environmental impacts have been attributed to the actual production of the PiB-aluminium sheet. This as no specific production process data are available. The environmental impact of aluminium reinforced PiB will thus be underestimated.

Characteristics of the sheet are:

weight[1]	2.53 kg/m^2
width	14 – 56 cm
length	500 or 1000 cm

The distance from aluminium mesh producer to producer of roofing sheets amounts to 250 km and from the PiB (polyisobutylene) bulk producer 100 km.

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[1] Measured and calculated value.

3.4.3 Application at the building

The expected service life of reinforced PiB flashings is 25 years. This means that during the service life of the building the product has to be installed three times. At each application the installation loss is estimated to be at 5%. For three applications 7.97 kg is needed to apply 1 m^2 of aluminium reinforced PiB sheet at an installed weight of 7.59 kg. The application losses are thus 0.38 kg.

3.4.4 Use of cavity wall sheets and flashing sheets

In this stage the sheets have a lifespan of 25 years, which means that the sheets will be replaced two times after the first installation during the building life span.

As no reliable data on the run-off for aluminium reinforced PiB are available, it has been assumed that no substances run off from the installed material.

3.4.5 Demolition and end-of-life

During the lifespan of the building two replacements are made. At the end-of-life of the building all sheets are removed during demolition of the building. The removed sheets are sent to waste treatment in accordance with the description given in section 3.2 General inventory data.

3.4.6 Flow chart and transport needs

From the preceding sections describing the life cycle of aluminium reinforced PiBsheet a flow chart has been distilled (see Figure 6).

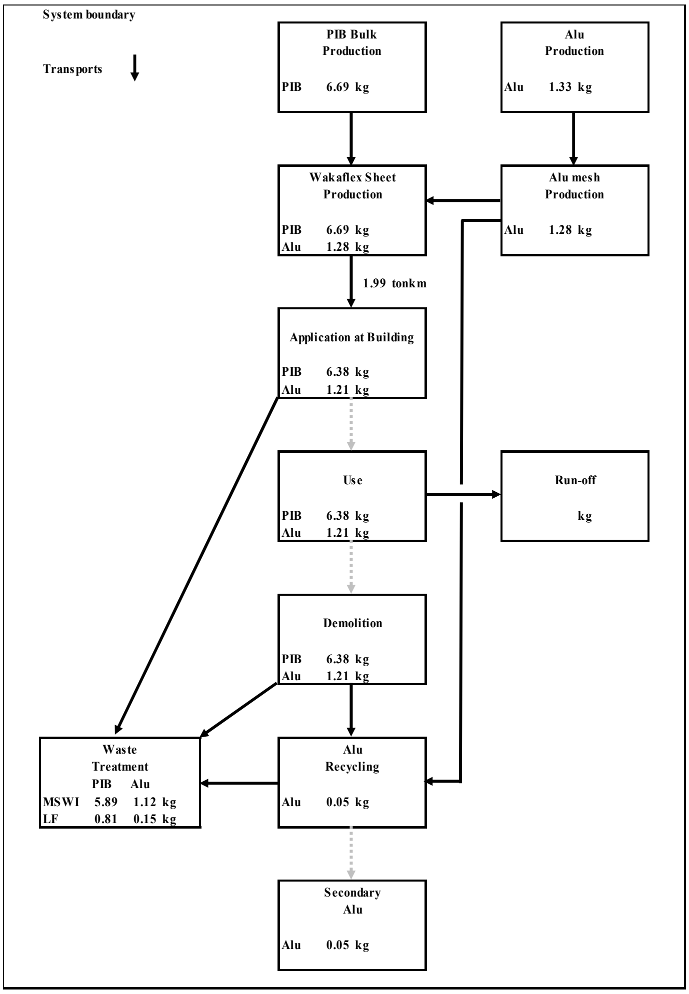

Figure 6 *Flow diagram of the life cycle aluminium reinforced PiB. 'Alu' stands for aluminium; 'MSWI' for municipal solid waste incinerator; 'LF' for landfill.*

Transport data with respect to production, use and discard of aluminium reinforced PiB used as damp proof course in buildings are shown in Table 7.

Table 7 *Transport data for the life cycle of aluminium reinforced PiB.*

From	**To**	**Distance (km)**	**Return**	**Tonkm**
Aluminium producer	Aluminium mesh producer	250		0.331
Aluminium mesh producer	Sheet producer	250		0.319
Aluminium mesh producer	Aluminium recycler	100	x	0.010
PiB bulk producer	Sheet producer	100	x	1.339
Wakaflex sheet producer	Building site	250		1.992
Building site	Waste incinerator	100	x	0.067
Building site	Landfill	50	x	0.005
Building site (demolition)	Waste incinerator	100	x	1.335
Building site (demolition)	Landfill	50	x	0.092

3.5 Aluminium reinforced SEBS modified bitumen

3.5.1 Production of raw materials

Aluminium reinforced SEBS modified bitumen consists of the following materials:
- SEBS (styrene ethylene/butylene styrene)
- bitumen
- aluminium
- sand and ground limestone.

SEBS is a thermoplastic elastomer that is used to modify the (elastic) properties of bitumen. The amount of SEBS added to bitumen is not known, but is likely not to exceed 20% by mass. For this study a content of 12% has been used. No public sources were found describing the exact production process and composition of SEBS modified bitumen. The LCI data for synthetic rubber and sealing bitumen from the Ecoinvent database [14] have been used.

3.5.2 Production of the cavity wall sheets and flashing sheets

The composition of the reinforced SEBS modified bitumen has been measured by ashing a sample and establishing the amounts of aluminium, modified bitumen and remaining inert materials. The sample that has been used is from the most recent Ubiflex product. This product consists of an aluminium mesh incorporated into the bitumen; one surface is coated with a sandy material [15].

It appeared that the material consisted of a perforated sheet of aluminium which contributes to 37% of the mass. The SEBS modified bitumen accounted for 62% of the total mass. The remaining 1% consisted of an inert material which consisted of Si, O and Ca [15]. It is likely that this is the sandy coating applied to one of the surfaces. The coating most likely consists of sand and ground limestone. For the LCI it has been assumed that it is made up 100% from sand.

It has been assumed that the SEBS modified bitumen consists of 18% SEBS and 82% bitumen.

The processes for forming the sheet out of the raw materials are not known; therefore no environmental impacts are accounted for. This may lead to some underestimation of the environmental impact.

Characteristics of the sheet are:

– weight[1]	3.260 kg/m^2
– width	15 – 100 cm
– length	600 or 1200 cm

The distance from aluminium sheet producer to producer of roofing sheets amounts to 250 km and 100 km for the SEBS and sand producer.

3.5.3 Application at the building

The average distance from sheet producer to building site amounts to 250 km. Application losses are 5%, which means that 10.27 kg is needed to apply 1 m^2 of aluminium reinforced SEBS sheet with a weight of 9.78 kg.
The losses of 0.49 kg are transported to the waste treatment.

3.5.4 Use of cavity wall sheets and flashing sheets

In this stage the sheets have an expected lifespan of 30 years, which means that the sheets will be replaced two times after the first installation during the building life span.

As no reliable data on the run-off of aluminium reinforced SEBS modified bitumen are available, it has been assumed that no substances run off from the installed material.

3.5.5 Demolition and end-of-life

All sheets removed during the service life of the building are collected for recovery and waste treatment. The aluminium part of the incinerated waste is recovered from the MSWI bottom ashes and recycled.

3.5.6 Flow chart and transport needs

From the preceding sections describing the life cycle of aluminium reinforced SEBS modified bitumen sheet a flow chart has been distilled (see Figure 7).

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[1] Measured value from sample of 80 by 120 mm.

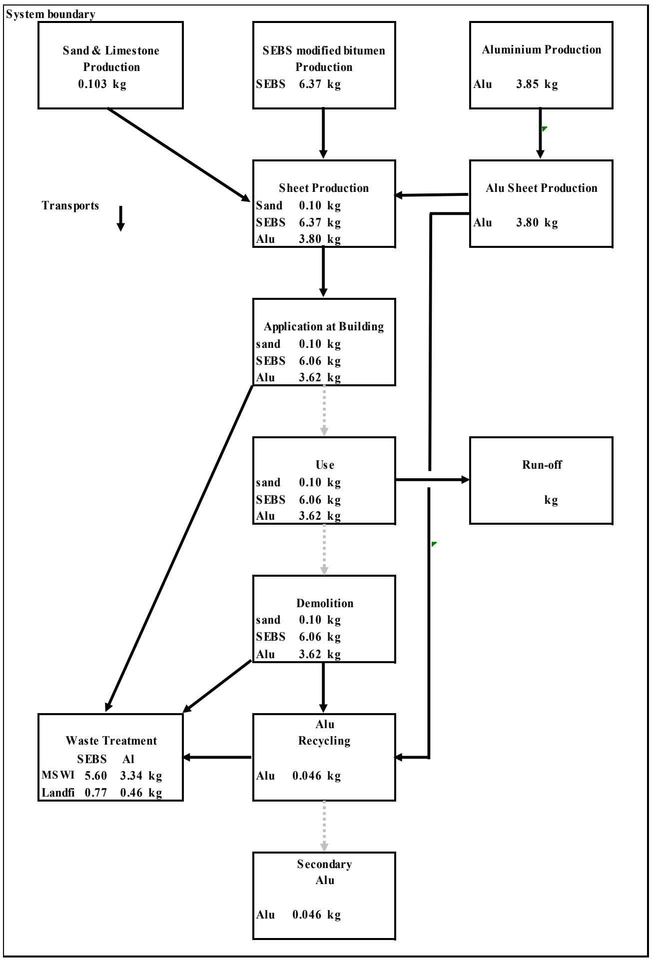

Figure 7 Flow diagram life cycle of aluminium reinforced SEBS modified bitumen. 'Alu' stands for aluminium; 'MSWI' for municipal solid waste incinerator; 'Landf for landfill.

In Table 8 the transport data with respect to production, use and discard of aluminium reinforced SEBS modified bitumen used as damp proof course in buildings are given.

Table 8 Transport data of the life cycle of aluminium reinforced SEBS modified bitumen.

From	To	Distance (km)	Return	Tonkm
Aluminium producer	Aluminium sheet producer	250		0.950
Aluminium sheet producer	Sheet producer	250		0.950
Aluminium sheet producer	Aluminium recycler	100	x	0.000
SEBS - bitumen producer	Sheet producer	100	x	1.274
Sheet producer	Building site	250		2.542
Building site	Aluminium recycler	100	x	0.0077
Building site	Waste incinerator	150	x	0.128
Building site	Landfill	100	x	0.012
Building site (demolition)	Waste incinerator	150	x	2.554
Building site (demolition)	Landfill	100	x	0.234

3.6 Aluminium reinforced EPDM

3.6.1 Production of raw materials

The sheets of aluminium reinforced EPDM are made of the following materials:
- Aluminium (mesh)
- EPDM (Ethylene Propylene Diene Monomer synthetic rubber)

The main raw material used is EPDM; the aluminium is added to give the composite material enough stiffness and mass.

To give EPDM its right properties some additives, like carbon black, paraffin oil, zinc, sulphur and mineral oil, are used. Amounts needed for the production are based upon Kirk Othmer (1992) and Hertel (1997). In Appendix C detailed data can be found.

3.6.2 Production of the cavity wall sheets

The weather-proofing sheets are produced by melting and vulcanising EPDM, incorporating the aluminium mesh, sanding one surface and cutting the sheets to the right size [1]. Aluminium reinforced EPDM is only used for cavity wall applications.

Characteristics of the sheet are [1]:

– weight[1]	2.42 kg/m^2
– composition	90% EPDM 10% aluminium sheet

3.6.3 Application at the building

The application losses are 5%, which means that 7.62 kg is needed to apply 1 m^2 of aluminium reinforced EPDM sheet for three installations over the lifespan of the building.

3.6.4 Use of cavity wall sheets and flashing sheets

In this stage the sheets have a lifespan of 30 years, which means that the sheets will be replaced two times after the first installation during the building life span.
The leaching rate is 0 g/m^2/year.

3.6.5 Demolition and end-of-life

Thirty years after installation, 60 years after installation and finally after 75 years when the building is demolished, the used sheets are removed and sent to waste treatment. The aluminium part of the removed waste is reclaimed from the MSWI bottom ashes for recycling.

3.6.6 Flow chart and transport needs

From the preceding sections describing the life cycle of aluminium reinforced EPDM sheet a flow chart has been distilled (see Figure 8).

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[1] Calculated value.

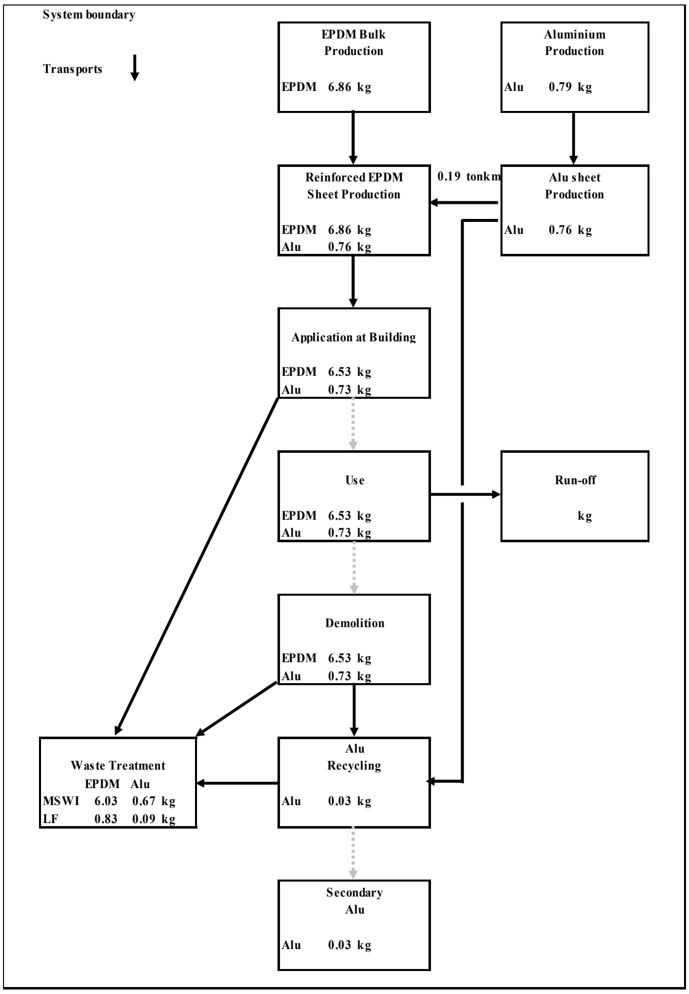

Figure 8 *Flow diagram life cycle of aluminium reinforced EPDM. 'Alu' stands for aluminium; 'MSWI' for municipal solid waste incinerator; 'LF' for land-fill.*

Transport data with respect to production, use and discard of aluminium reinforced EPDM used as damp proof course in buildings are shown in Table 9.

Table 9 Transport data of aluminium, EPDM and reinforced EPDM sheet.

From	To	Distance (km)	Return	Tonkm
Aluminium producer	Aluminium sheet producer	250		0.198
Aluminium sheet producer	Reinforced EPDM sheet producer	250		0.191
Aluminium sheet producer	Aluminium recycler	100	x	0.006
EPDM producer	Reinforced EPDM sheet producer	100	x	1.372
Reinforced EPDM sheet producer	Building site	250		1.906
Building site	Waste incinerator	150	x	1.340
Building site	Landfill	100	x	0.092

3.7 PVC

3.7.1 Production of raw materials

The PVC used for flashings is plasticized PVC. For the production of the PVC sheets the basic material consists of:

– PVC	40%
– Plasticiser	21%
– Stabiliser (ZnO)	2%
– Lime	38%

This composition has been based on the average composition of PVC used for cable sheathing and flooring [18] as no specific data for PVC for flashing are available. For the plasticizer DEHP (di-2-ethylhexyl phthalate) has been used. The LCI data for this substance have been used from [19].

3.7.2 Production of the cavity wall sheets and flashing sheets

The PVC sheets are produced from the raw materials mentioned before. Characteristics of the PVC sheets are:

– thickness	1.3 – 2.0 mm
– weight	2.36 kg/m^2

3.7.3 Application at the building

As the application losses are 5% and the expected lifespan of the product is 20 years, 9.91 kg is needed to apply 1 m^2 of PVC sheet during 75 years. The losses of 0.47 kg are transported to waste treatment.

3.7.4 Use of cavity wall sheets and flashing sheet

In this stage the sheets have a lifespan of 20 years. As no reliable data on the run-off of PVC are available, it has been assumed that the run-off rate is 0 g/m^2/year.

3.7.5 Demolition and end-of-life

Thirty years after installation, 60 years after installation and finally after 75 years when the building is demolished, the used PVC sheets are removed and sent to waste treatment.

3.7.6 Flow chart and transport needs

From the preceding sections describing the life cycle of PVC sheet a flow chart has been distilled (see Figure 9).

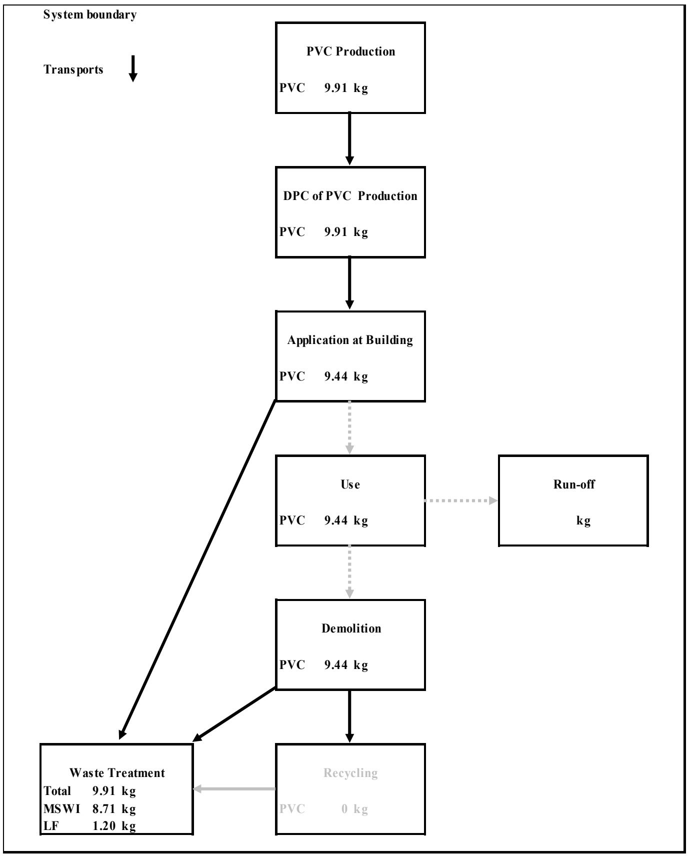

Figure 9 Flow diagram of the PVC weather-proofing life cycle. 'MSWI' stands for municipal solid waste incinerator; 'LF' for landfill.

The transport data with respect to production, use and discard of PVC sheet used as weather-proofing in buildings are shown in Table 10.

Table 10 Transport data of PVC sheet.

From	To	Distance (km)	Return	Tonkm
PVC producer	Sheet producer	100		0.991
Sheet producer	Building site	250	x	4.956
Building site	Waste incinerator	150	x	0.124
Building site	Landfill	100	x	0.011
Building site (demolition)	Waste incinerator	150	x	2.490
Building site (demolition)	Landfill	100	x	0.228

3.8 Glass fibre reinforced polyester

3.8.1 Production of raw materials

Glass fibre reinforced polyester (GRP) consists of the following materials:
- polyester
- glass fibre

The LCI data for these two materials have been selected from the Ecoinvent database [14].

3.8.2 Production of the cavity wall sheets and flashing sheets

Chopped strand mat is the most widely used form of glass reinforcement, especially in sheet materials. The strands (2 to 5 cm long) are distributed randomly. The glass content of GRP reinforced with chopped strand mat generally varies between 25 and 35%. In this study a share of 30% has been chosen.

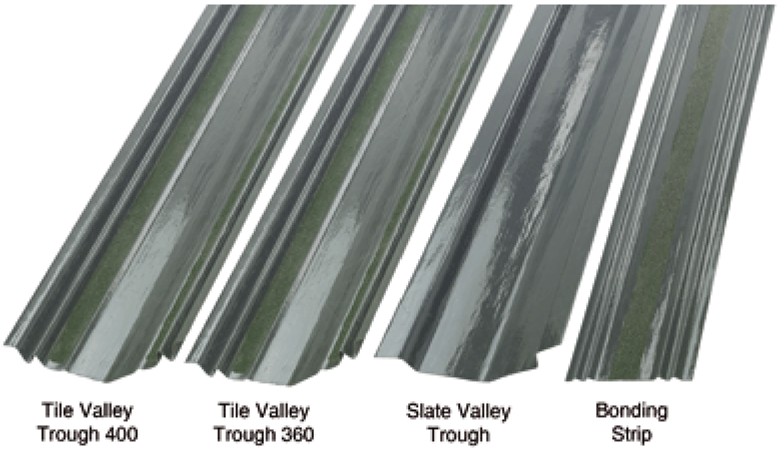

Figure 10 Examples of valley troughs made from GRP by Klober Ltd.

Characteristics of the sheet are based on a tile valley trough (VAL 360), manufactured by Klober Ltd.:

– weight[1]	2.001 kg/m^2
– thickness	1.1 mm
– composition	70% polyester 30% glass fibre

For the calculation of the mass per m^2 the width of the trough when pressed down on a flat surface (approx. 38.5 cm) has been used.

The production of the GRP valley trough has been based on the Ecoinvent LCI data [14] for the production of GRP. In these data a production efficiency of 95% has been assumed. In these data only the use of raw materials and the emission of styrene have been included; process specific energy consumption has not been included.

3.8.3 Application at the building

The application losses are 5%, meaning that 6.3 kg is needed to apply 1 m^2 of glass reinforced polyester sheet for three applications.

3.8.4 Use of cavity wall sheets and flashing sheets

In this stage the sheets have a lifespan of 30 years, which means that the sheets will be replaced two times after the first installation during the building life span.
No substances are expected to leach from the glass reinforced polyester.

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[1] Calculated value.

3.8.5 Demolition and end-of-life

The sheets that are removed at the end of their lifespan and the sheets that are removed during demolition of the building after 75 years are sent to waste treatment.

3.8.6 Flow chart and transport needs

From the preceding sections describing the life cycle of glass fibre reinforced PVC sheet a flow chart has been distilled (see Figure 11).

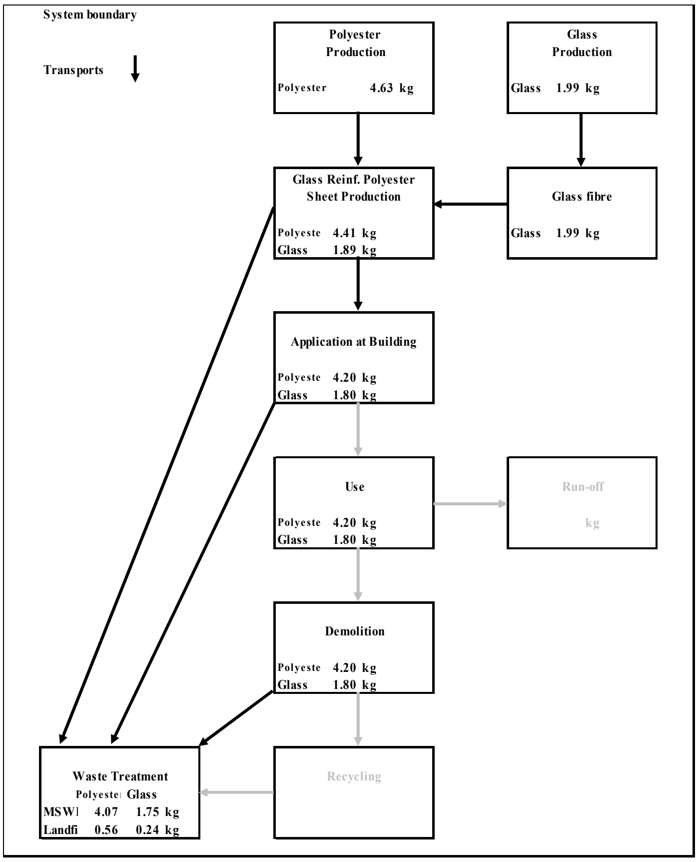

Figure 11 Flow diagram life cycle of glass fibre reinforced polyester. 'MSWI' stands for municipal solid waste incinerator; 'Landf' for landfill.

Table 11 shows the transport data with respect to production, use and discard of glass fibre reinforced polyester used as damp proof course in buildings.

Table 11 Transport data of glass, glass fibre and GRP sheet.

From	To	Distance (km)	Return	Tonkm
Glass producer	Glass fibre producer	250		0.496
Glass fibre producer	GRP producer	250		0.496
Plastic producer	GRP producer	100	x	0.926
GRP producer	Building site	250		1.575
Building site	Waste incinerator	150	x	0.079
Building site	Landfill	100	x	0.007
Building site (demolition)	Waste incinerator	150	x	1.583
Building site (demolition)	Landfill	100	x	0.145

4. Environmental impact assessment methodology

4.1 Introduction to the impact assessment method

After having compiled the LCI results giving all the in- and outputs of each system they are translated to environmental impacts by applying a life cycle impact assessment method. In this case the widely used and accepted CML2 method [3] has been used. The method distinguishes a number of baseline impact categories which should be included in a comparative LCA. The environmental impacts considered are given in Table 12.

Table 12 Overview of environmental impacts in the CML2 method.

Environmental impacts	Abbreviation	Unit
Abiotic Resource Depletion Potential	ADP	kg Sb eq.
Global Warming Potential	GWP	kg CO_2 eq.
Ozone Depletion Potential	ODP	kg CFC-11 eq.
Human Toxicity Potential	HTP	kg 1,4-DB eq.
Fresh water Aquatic Eco-toxicity Potential	FAETP	kg 1,4-DB eq.
Marine aquatic Eco-toxicity Potential	MAETP	kg 1,4-DB eq.
Terrestrial Eco-toxicity Potential	TETP	kg 1,4-DB eq.
Photochemical Ozone Creation Potential	POCP	kg C_2H_2 eq.
Acidification Potential	AP	kg SO_2 eq.
Eutrophication Potential	EP	kg PO_4^{3-} eq.

The mineral resources depletion potential (ADP) is based on the amount of these resources in the earth’s crust.

A further introduction of the CML 2 method is given in Appendix B.

4.2 Adjustment of the impact assessment method

In recent years it has become clear that the toxicity related impact of especially metals was inadequately addressed in the most recent CML2 method used for the impact assessment in numerous LCAs. In the Declaration of Apeldoorn [23] this problem was addressed by a group of specialists. One of the points to be improved is to base the impact on the HC50[1] rather than on the PNEC for a given substance. In this study a full adaptation of the CML2 method to this point is far beyond reach. However, an approximation was made by establishing which ten substances contributed most to the toxicity impact of all products studied in this report. For

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[1] HC50 is the geometric mean of the dose-response curve for multiple organisms. This is a more robust representation of the (eco-)toxicity than that of the predicted no-effect concentration (PNEC) or no observed effect concentration (NOEC) values as uncertainty is reduced.

these substances the HC50 values available from literature were used, or in case this proved to be impossible EC50 or LC50 values were used.

The pre-assessment showed that the ten combinations of substance - initial emission compartment – impact category shown in Table 13 had the highest contribution.

Table 13 The ten substances most contributing to the toxicity based impact categories.

Substance	Initial compartment	Impact category	Relative impact on category (%)
Copper, ion	Water	FAETP	15.9
Nickel, ion	Water	FAETP	12.1
Vanadium, ion	Water	FAETP	48.6
PAHs	Air	HTP	42.4
Lead	Soil	HTP	15.8
Hydrogen fluoride	Air	MAETP	50.4
Beryllium	Water	MAETP	11.4
Vanadium, ion	Water	MAETP	13.7
Mercury	Air	TETP	40.9
Chromium VI	Soil	TETP	17.9

HC50 values were sought in public literature. In case the HC50 value was not available for a substance the arrhythmic mean of EC50 values or LC50 values from reports and databases [8], [25], [26], [27] and [28] was calculated and used. The value of the HC50 for each substance is presented in Appendix D.

Also for the reference substance used in the toxicity impact categories of CML2, 1,4 – dichlorobenzene, the HC50 values were obtained. From this improved characterisation factors for the top ten contributing substances could be calculated. The new factors (see Table 14) have been used in the results shown in the environmental impact assessment (see chapter 5).

Table 14 Improved characterisation factors for the ten substances most contributing to the toxicity based impact categories.

Substance	Initial compartment	Impact category	CML2 factor	Improved factor
Copper, ion	Water	FAETP	1.16E+03	6.57E+01
Nickel, ion	Water	FAETP	3.24E+03	3.96E+01
Vanadium, ion	Water	FAETP	8.97E+03	1.06E+01
PAHs	Air	HTP	8.11E+00	1.72E-02
Lead	Soil	HTP	3.28E+03	1.77E+01
Hydrogen fluoride	Air	MAETP	4.07E+07	9.89E+06
Beryllium	Water	MAETP	5.39E+08	1.34E+06
Vanadium, ion	Water	MAETP	8.58E+06	1.01E+05
Mercury	Air	TETP	2.83E+04	-
Chromium VI	Soil	TETP	6.30E+03	-

For all of the substances a strong decrease in characterisation factor shows. For the mercury and chromium VI an improved characterisation factor for TETP could not be calculated as it was not possible to calculate a reliable HC50 value due to the lack of data.

Application of the adjusted method for all products leads to significant reductions of the impact for FAETP and MAETP (see Figure 12). For HTP the changes are the strongest for the aluminium reinforced products. For TETP no effect in the impact is seen as the characterisation factors for Hg and Cr(IV) were not changed (see Table 14).

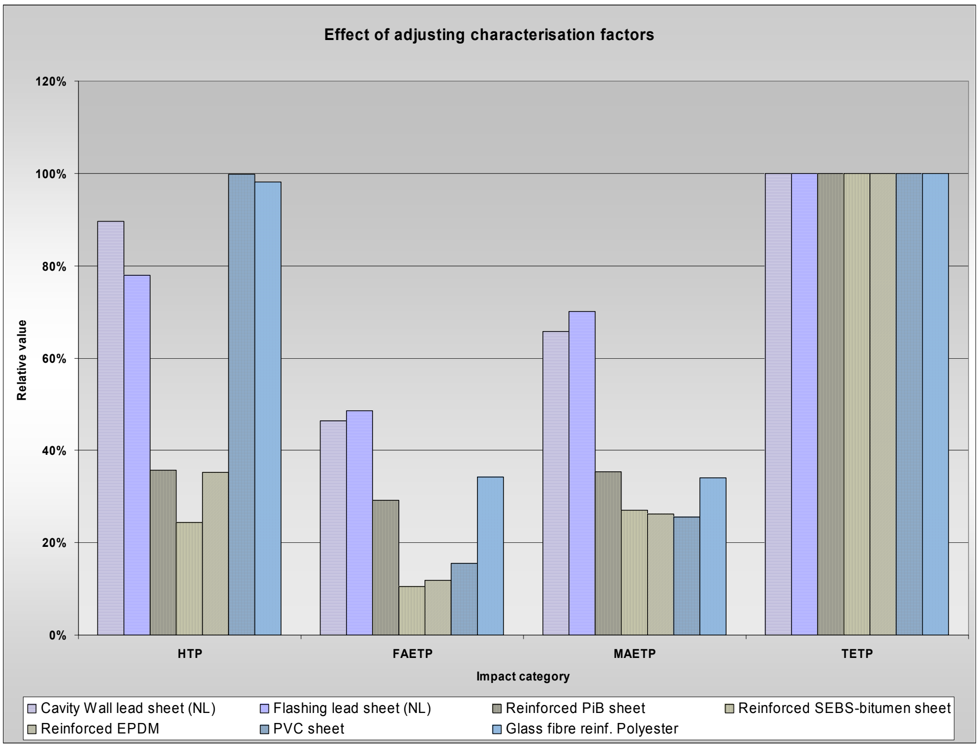

Figure 12 Effect of adjusting the toxicity based impact categories (HTP, FAETP, MAETP and TETP) for the top ten contributing substances. The example shows the comparison of the original method (CML2) and the adjusted method for all materials in the Netherlands.

4.3 Shadow price based impact assessment

In comparative LCAs one of the drawbacks is how to compare the different alternatives with one another. In the simple case that alternative 'A' scores lower for all ten impact categories compared to alternative 'B' the comparison is easy: 'A' is the preferred option. Most often, the results show that 'A' is better for impact 'x' but has a higher impact for impact 'z'. In this case weighing of the impact categories is a possibility, but this introduces subjectivity as internationally accepted weighing factors are not available.

A solution is to base the multiple impact category comparison on the shadow prices for these impacts [29]. These shadow prices are based on the current policy aims for emission levels for specific substances. The emissions of the substances in question can be related to each impact category of the CML2 method. As these policy aims are not yet fulfilled emission reduction measures have to be taken. Starting from the current (Dutch) emission levels the emission reduction measures that have to be taken to achieve the aim are selected, starting with the cheapest measure. The last measure that has to be taken to achieve the aim is the base for the shadow price. The expenditure needed for this measure per unit reduction per impact category is the shadow price. For GWP a shadow price of 0.05 €/kg CO_2 eq. was obtained in this way, while for FAETP a shadow price of 0.04 €/kg 1,4-DCB eq. was found. The set of shadow prices obtained, can be used as an environmental and economic yardstick of present policies to assess environmental profiles based on the current policies and the economy of emission reduction measures.

5. Environmental impact assessment

5.1 Introduction

In the figures and tables in this chapter the several life cycle stages are referred to by their numbers:

1. Production of raw materials
2. Production of the cavity wall sheets and flashing sheets
3. Application at the building
4. Use of cavity wall sheets and flashing sheets
5. Demolition and end-of-life.

5.2 Lead sheet

5.2.1 Lead sheet applied in cavity walls

The environmental impact of lead sheet applied in cavity walls in the Netherlands (see Figure 13 and Table 15) shows the production of primary and secondary lead; the production of the sheet; and the use phase as the most contributing (>25% impact) life cycle stages. The use phase, where the emission of lead through the run-off occurs, is only significant for TETP. The run-off emission explains here 19% of this impact category.

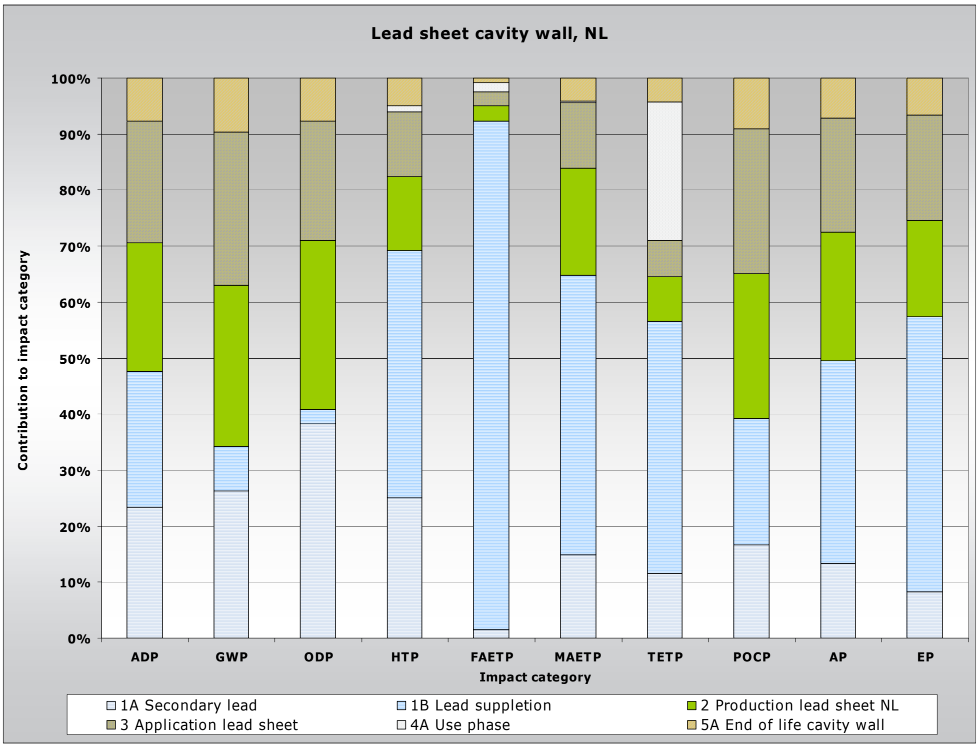

Figure 13 Environmental impacts of lead sheet applied in cavity walls in the Netherlands. The impacts are relative to the total impact per category.

Table 15 Characterised environmental impacts and the environmental shadow costs (bottom row) for lead sheet applied in cavity walls in the Netherlands.

Impact	Total	1A Secondary lead (kg)	1B Lead replenishment	2 Production lead sheet NL	3 Application lead sheet NL	4 Use phase cavity wall	5 End of life cavity wall NL
ADP kg Sb eq	6.37E-02	1.49E-02	1.54E-02	1.47E-02	1.39E-02		4.88E-03
GWP kg CO_2 eq	7.30E+00	1.92E+00	5.82E-01	2.10E+00	2.00E+00		7.04E-01
ODP kg CFC-11 eq	1.25E-06	4.76E-07	3.21E-08	3.77E-07	2.66E-07		9.55E-08
HTP kg 1,4-DB eq	3.96E+00	9.91E-01	1.75E+00	5.23E-01	4.55E-01	4.62E-02	1.94E-01
FAETP kg 1,4-DB eq	1.96E+00	3.05E-02	1.78E+00	5.44E-02	4.80E-02	3.22E-02	1.73E-02
MAETP kg 1,4-DB eq	1.57E+03	2.34E+02	7.84E+02	3.01E+02	1.84E+02	3.73E+00	6.57E+01
TETP kg 1,4-DB eq	5.73E-02	6.60E-03	2.58E-02	4.59E-03	3.70E-03	1.42E-02	2.48E-03
POCP kg C_2H_4	3.69E-03	6.13E-04	8.32E-04	9.57E-04	9.53E-04		3.35E-04
AP kg SO_2 eq	5.36E-02	7.18E-03	1.94E-02	1.23E-02	1.09E-02		3.85E-03
EP kg PO_4^{3-} eq	1.16E-02	9.64E-04	5.70E-03	1.99E-03	2.18E-03		7.67E-04
Shadow costs	**€1.32**	**€0.25**	**€0.48**	**€0.25**	**€0.23**	**€0.02**	**€0.08**

The shadow costs (see Table 15) show that the production of primary lead, used to replenish the lead losses from the life cycle, dominates the environmental impact over the other phases. The impact categories that contribute most to the shadow costs are GWP, HTP and AP (see Figure 14). The total shadow cost is €1.32 over the whole life cycle.

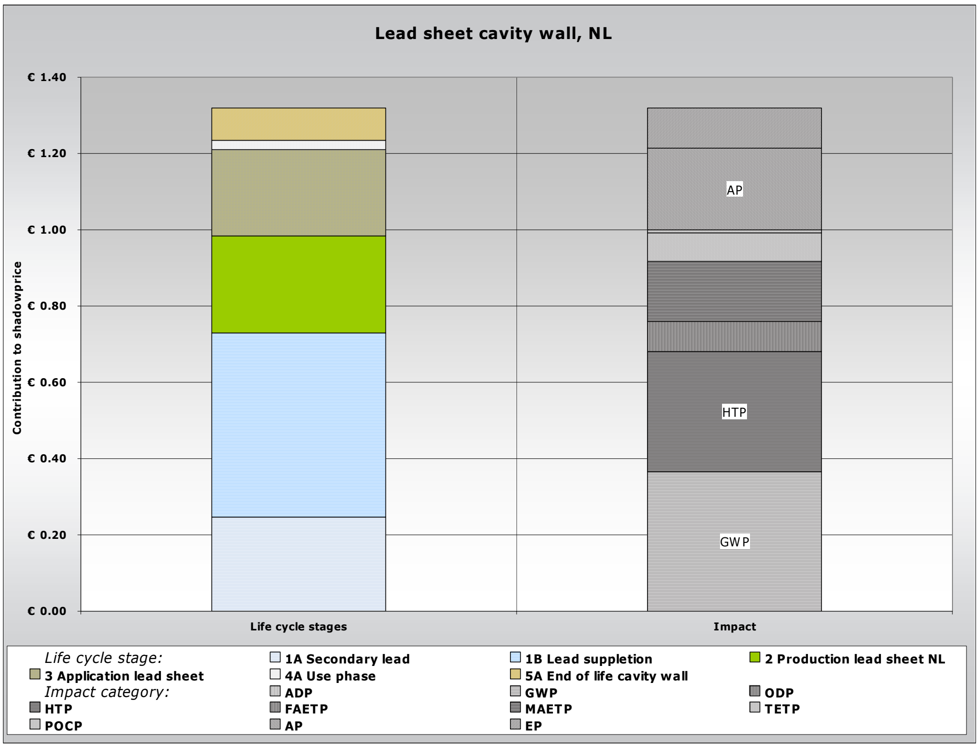

Figure 14 The environmental impact expressed in shadow costs (€) of lead sheet applied in cavity walls in the Netherlands. The left bar shows the contribution of the single life cycle phases; the right bar shows the contribution of each impact category.

In the German situation transport distances from the producer to the end user and from the end user to the recycler are larger then in the Netherlands (see section 3.3.6). This will lead to an increased environmental impact. The increase in impact compared to the Dutch situation takes place in the production of lead sheet stage and in the application stage as can be seen from comparing Figure 13 and Figure 15. It is more easily clear when the shadow cost based Figure 16 is observed.

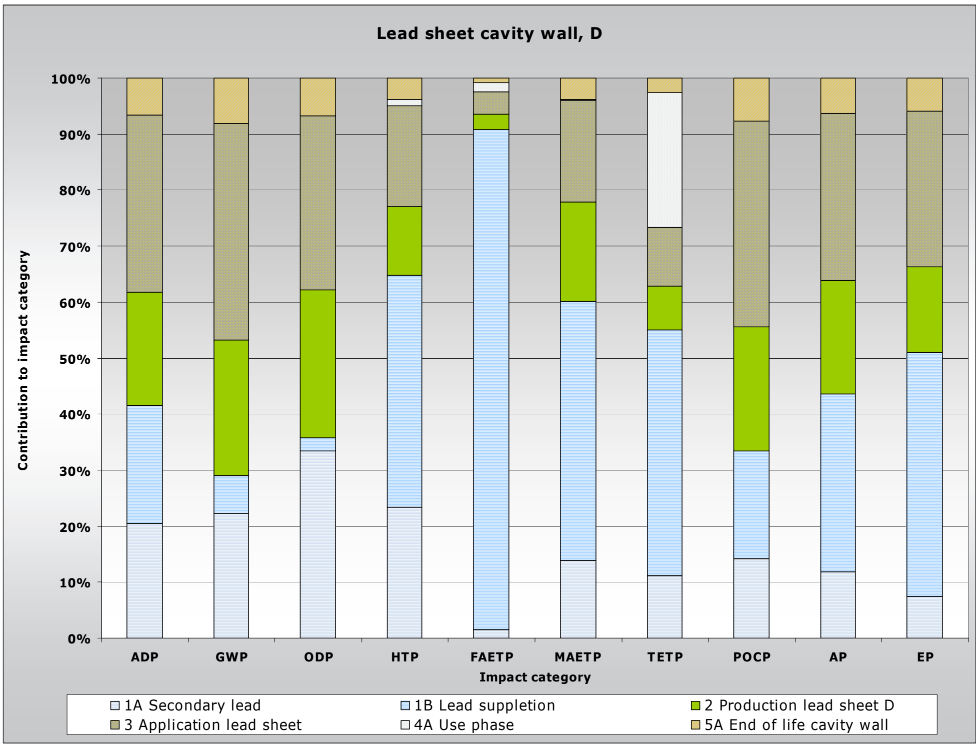

Figure 15 *Environmental impacts of lead sheet applied in cavity walls in Germany. The impacts are relative to the total impact per category.*

Table 16 *Characterised environmental impacts and the environmental shadow costs for lead sheet applied in cavity walls in Germany.*

Impact	**Total**	**1A Secondary lead (kg)**	**1B Lead replenishment**	**2 Production lead sheet D**	**3 Application lead sheet D**	**4A Use phase cavity wall**	**5A End of life cavity wall D**
ADP kg Sb eq	7.29E-02	1.49E-02	1.54E-02	1.47E-02	2.31E-02		4.85E-03
GWP kg CO_2 eq	8.63E+00	1.92E+00	5.82E-01	2.10E+00	3.33E+00		7.01E-01
ODP kg CFC-11 eq	1.42E-06	4.76E-07	3.21E-08	3.77E-07	4.43E-07		9.52E-08
HTP kg 1,4-DB eq	4.23E+00	9.91E-01	1.75E+00	5.23E-01	7.58E-01	4.62E-02	1.65E-01
FAETP kg 1,4-DB eq	1.99E+00	3.05E-02	1.78E+00	5.44E-02	8.00E-02	3.22E-02	1.71E-02
MAETP kg 1,4-DB eq	1.69E+03	2.34E+02	7.84E+02	3.01E+02	3.06E+02	3.73E+00	6.47E+01
TETP kg 1,4-DB eq	5.89E-02	6.60E-03	2.58E-02	4.59E-03	6.16E-03	1.42E-02	1.54E-03
POCP kg C_2H_4	4.32E-03	6.13E-04	8.32E-04	9.57E-04	1.59E-03		3.34E-04
AP kg SO_2 eq	6.09E-02	7.18E-03	1.94E-02	1.23E-02	1.82E-02		3.84E-03
EP kg PO_4^{3-} eq	1.31E-02	9.64E-04	5.70E-03	1.99E-03	3.63E-03		7.65E-04
Shadow costs	**€1.47**	**€0.25**	**€0.48**	**€0.25**	**€0.38**	**€0.02**	**€0.08**

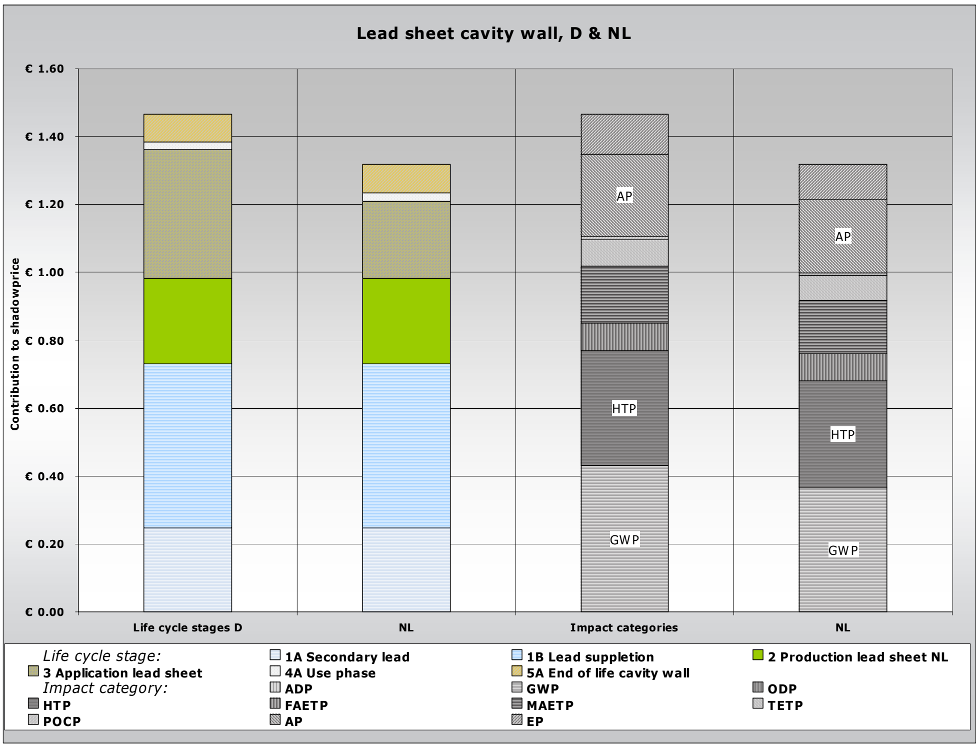

Figure 16 *The comparison of the shadow costs (€) of lead sheet applied in cavity walls in Germany and in the Netherlands. The left two bars show the contribution of the single life cycle phases of respectively the German and Dutch situation; the right two bar show the contribution of each impact category.*

5.2.2 Lead sheet applied as flashings

The main difference between cavity wall application and the application of lead sheet as flashing in wall/roof transitions is that the exposed surface is much larger (95% instead of 10%). This will increase the amount of the run-off lead emission and so increase of the impact of the use stage is to be expected. However, the amount of lead that is in the run-off is small at 6.6 g compared to the installed amount of lead (18 kg).

Due to the higher exposed surface the amount of lead corroded also increases compared to the cavity wall application. Instead of 33 gram over 75 years 314 gram is now lost to corrosion. This reduces the amount of lead to be recycled.

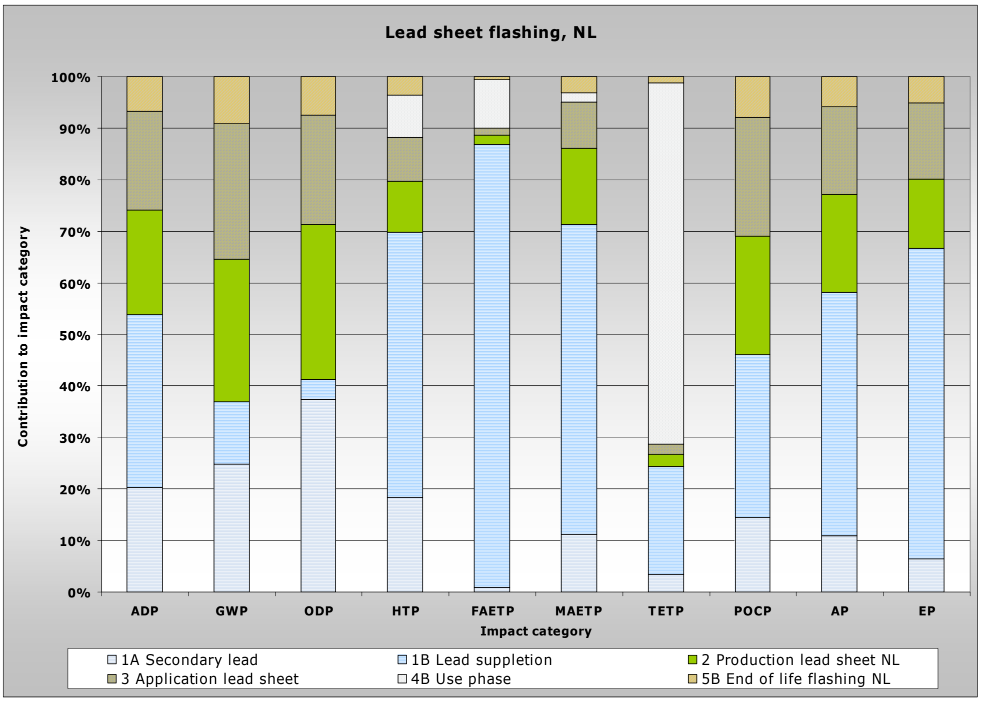

Figure 17 Environmental impacts of lead sheet applied in wall/roof situations in the Netherlands. The impacts are relative to the total impact per category.

The increase of run-off shows the increased importance of the use phase, compared to the application in cavity walls, (see Figure 13 and Figure 17). The use phase now has a contribution of 70% to TETP.

Table 17 Characterised environmental impacts and the environmental shadow costs for lead sheet applied in wall/roof situations in the Netherlands.

Impact	Total	1A Secondary lead (kg)	1B Lead replenishment	2 Production lead sheet NL	3 Application lead sheet NL	4A Use phase flashing	5A End of life flashing NL
ADP kg Sb eq	7.21E-02	1.47E-02	2.41E-02	1.47E-02	1.39E-02		4.80E-03
GWP kg CO_2 eq	7.59E+00	1.89E+00	9.11E-01	2.10E+00	2.00E+00		6.93E-01
ODP kg CFC-11 eq	1.25E-06	4.68E-07	5.03E-08	3.77E-07	2.66E-07		9.40E-08
HTP kg 1,4-DB eq	5.32E+00	9.74E-01	2.74E+00	5.23E-01	4.55E-01	4.39E-01	1.91E-01
FAETP kg 1,4-DB eq	3.24E+00	3.00E-02	2.79E+00	5.44E-02	4.80E-02	3.06E-01	1.70E-02
MAETP kg 1,4-DB eq	2.04E+03	2.30E+02	1.23E+03	3.01E+02	1.84E+02	3.54E+01	6.47E+01
TETP kg 1,4-DB eq	1.92E-01	6.49E-03	4.04E-02	4.59E-03	3.70E-03	1.34E-01	2.44E-03
POCP kg C_2H_4	4.15E-03	6.03E-04	1.30E-03	9.57E-04	9.53E-04		3.30E-04
AP kg SO_2 eq	6.44E-02	7.06E-03	3.04E-02	1.23E-02	1.09E-02		3.79E-03
EP kg PO_4^{3-} eq	1.48E-02	9.48E-04	8.92E-03	1.99E-03	2.18E-03		7.55E-04
Shadow costs	**€1.79**	**€0.24**	**€0.76**	**€0.25**	**€0.23**	**€0.23**	**€0.08**

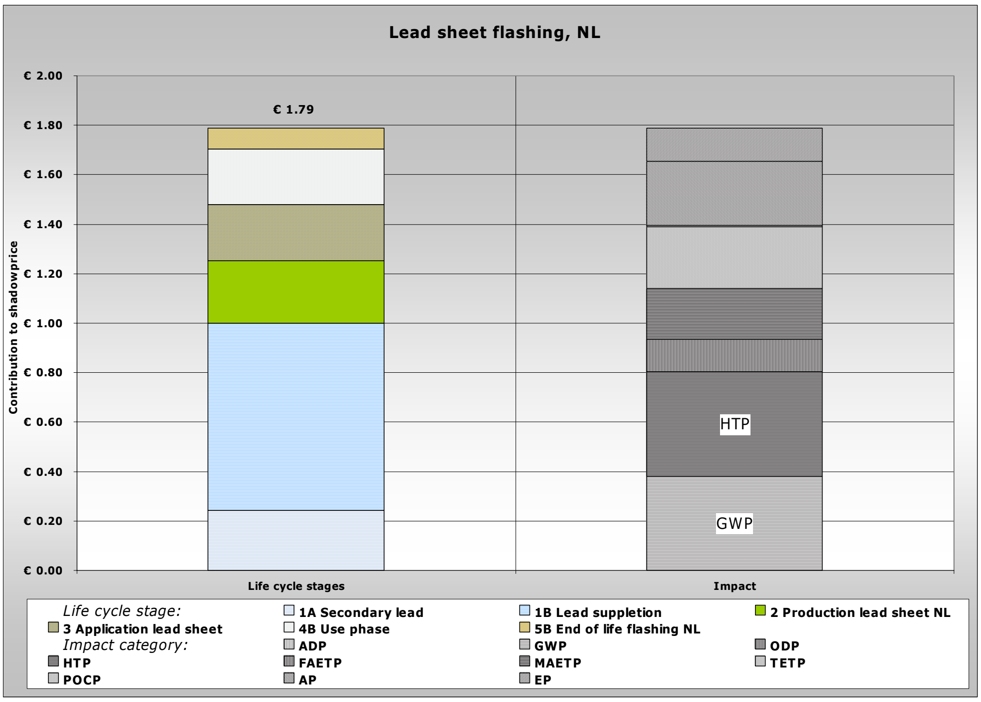

Figure 18 The environmental impact expressed in shadow costs (€) of lead sheet applied in wall/roof situations in the Netherlands. The left bar shows the contribution of the single life cycle phases; the right bar shows the contribution of each impact category.

The shadow costs (see Table 15 and Figure 18) shows that the replenishment by primary lead is the most contributing process. The human toxicity potential and the global warming potential are the most contributing impacts.

As for the lead sheet applied in cavity walls the transport distances from the producer to the end user and from the end user to the recycler are larger for Germany then for the Netherlands (see section 3.3.6) This will lead to an increased environmental impact (see Figure 19 and Table 18).

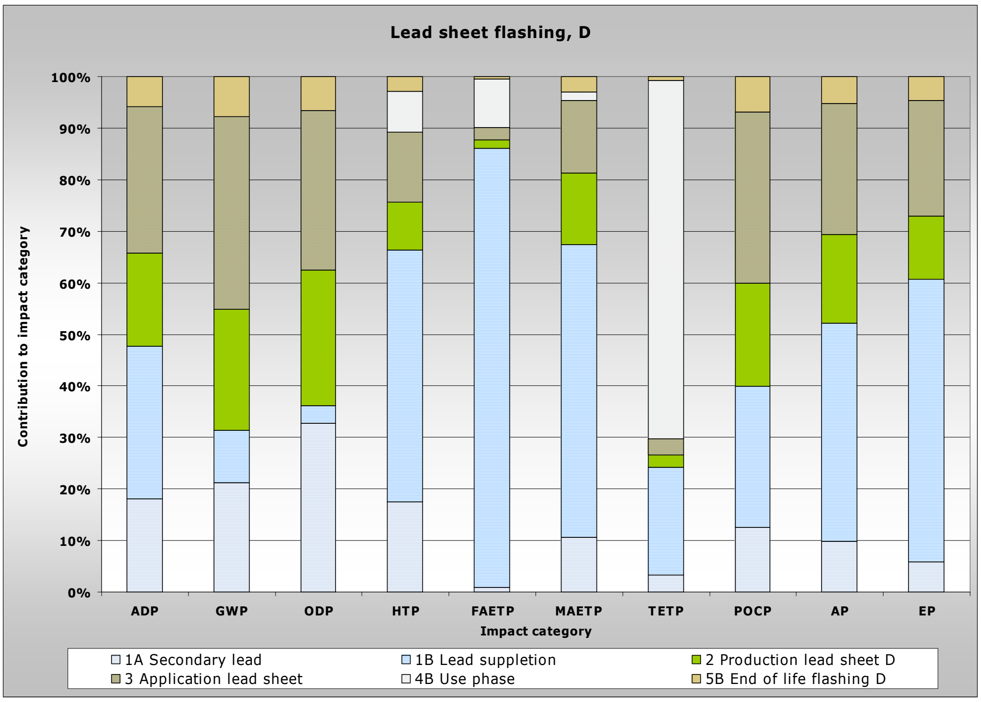

Figure 19 *Environmental impacts of lead sheet applied in wall/roof situations in Germany. The impacts are relative to the total impact per category.*

Table 18 Characterised environmental impacts and the environmental shadow costs for lead sheet applied in wall/roof situations in Germany.

Impact	Total	1A Secondary lead (kg)	1B Lead replenishment	2 Production lead sheet D	3 Application lead sheet D	4A Use phase flashing	5A End of life flashing D
ADP kg Sb eq	8.13E-02	1.47E-02	2.41E-02	1.47E-02	2.31E-02		4.77E-03
GWP kg CO_2 eq	8.92E+00	1.89E+00	9.11E-01	2.10E+00	3.33E+00		6.88E-01
ODP kg CFC-11 eq	1.43E-06	4.68E-07	5.03E-08	3.77E-07	4.43E-07		9.35E-08
HTP kg 1,4-DB eq	5.59E+00	9.74E-01	2.74E+00	5.23E-01	7.58E-01	4.39E-01	1.62E-01
FAETP kg 1,4-DB eq	3.27E+00	3.00E-02	2.79E+00	5.44E-02	8.00E-02	3.06E-01	1.68E-02
MAETP kg 1,4-DB eq	2.16E+03	2.30E+02	1.23E+03	3.01E+02	3.06E+02	3.54E+01	6.35E+01
TETP kg 1,4-DB eq	1.94E-01	6.49E-03	4.04E-02	4.59E-03	6.16E-03	1.34E-01	1.51E-03
POCP kg C_2H_4	4.78E-03	6.03E-04	1.30E-03	9.57E-04	1.59E-03		3.28E-04
AP kg SO_2 eq	7.17E-02	7.06E-03	3.04E-02	1.23E-02	1.82E-02		3.77E-03
EP kg PO_4^{3-} eq	1.62E-02	9.48E-04	8.92E-03	1.99E-03	3.63E-03		7.52E-04
Shadow costs	**€1.94**	**€0.24**	**€0.76**	**€0.25**	**€0.38**	**€0.23**	**€0.08**

The increase in impact compared to the Dutch situation takes place in the application stage as can be seen from the shadow costs based Figure 20. Due to the increased transport need the shadow costs increase from €1.78 to €1.94.

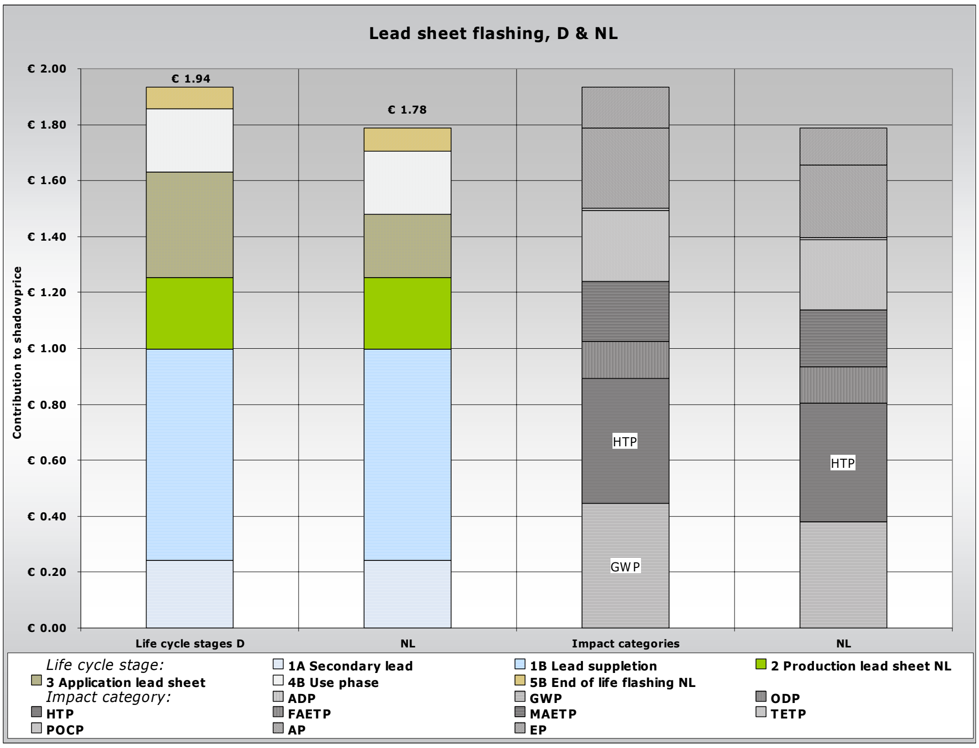

Figure 20 *The comparison of the shadow costs (€) of lead sheet applied in wall/roof situations in Germany (D) and in the Netherlands (NL). The left two bars show the contribution of the single life cycle phases of respectively the German and Dutch situation; the right two bars show the contribution of each impact category.*

5.3 Aluminium reinforced PiB

The production of PiB and the production of the aluminium mesh are the processes with the highest impact in the life cycle of the aluminium reinforced PiB (see Figure 21 and Table 19). The incineration of the sheet at the end-of-life stage is beneficial for the impact as the recuperation of the aluminium from the bottom ashes of the incinerator and the subsequent recycling gives a bonus for the avoided production of primary aluminium. The energy recovery from the PiB in the incinerator yields a minor benefit.

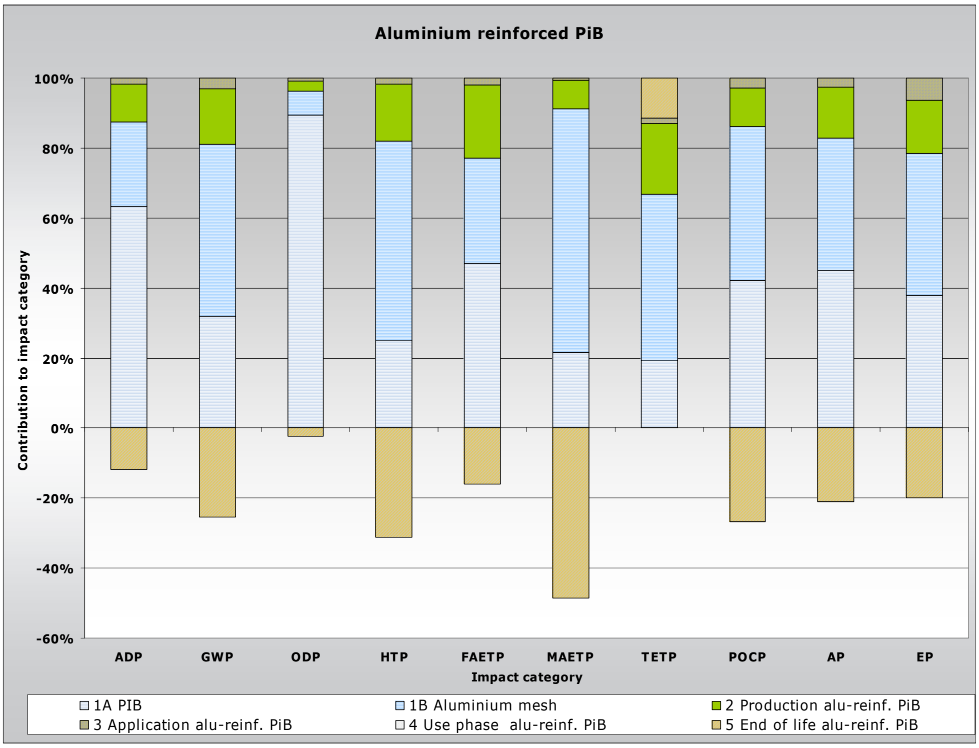

Figure 21 *Environmental impacts of aluminium reinforced PiB applied as weather-proofing in the Netherlands. The impacts are relative to the total impact per category.*

Table 19 Characterised environmental impacts and the environmental shadow costs for aluminium reinforced PiB applied as weather-proofing in the Netherlands.

Impact	Total	1A PIB (kg)	1B Aluminium mesh	2 Production alu-reinf. PiB	3 Application alu-reinf. PiB	4 Use phase alu-reinf. PiB	5 End of life alu-reinf. PiB
ADP kg Sb eq	2.50E-01	1.79E-01	6.92E-02	3.05E-02	4.87E-03		-3.35E-02
GWP kg CO_2 eq	1.76E+01	7.56E+00	1.15E+01	3.77E+00	7.03E-01		-6.01E+00
ODP kg CFC-11 eq	9.64E-06	8.83E-06	6.88E-07	2.73E-07	9.33E-08		-2.37E-07
HTP kg 1,4-DB eq	6.45E+00	2.34E+00	5.33E+00	1.53E+00	1.60E-01		-2.91E+00
FAETP kg 1,4-DB eq	6.93E-01	3.87E-01	2.49E-01	1.71E-01	1.69E-02		-1.31E-01
MAETP kg 1,4-DB eq	5.12E+03	2.16E+03	6.90E+03	8.21E+02	6.46E+01		-4.83E+03
TETP kg 1,4-DB eq	8.95E-02	1.72E-02	4.25E-02	1.82E-02	1.30E-03		1.02E-02
POCP kg C_2H_4	8.27E-03	4.76E-03	4.96E-03	1.24E-03	3.35E-04		-3.03E-03
AP kg SO_2 eq	1.14E-01	6.47E-02	5.45E-02	2.08E-02	3.84E-03		-3.03E-02
EP kg PO_4^{3-} eq	9.50E-03	4.49E-03	4.80E-03	1.80E-03	7.66E-04		-2.36E-03
Shadow costs	**€2.61**	**€1.13**	**€2.03**	**€0.53**	**€0.08**	**€0.00**	**-€1.16**

The production of the aluminium mesh and that of the PiB remain the main processes when the environmental impact is expressed in shadow costs (see Table 19 and Figure 22). The total shadow costs of €2.61 are for a large part related to global warming and human toxicity.

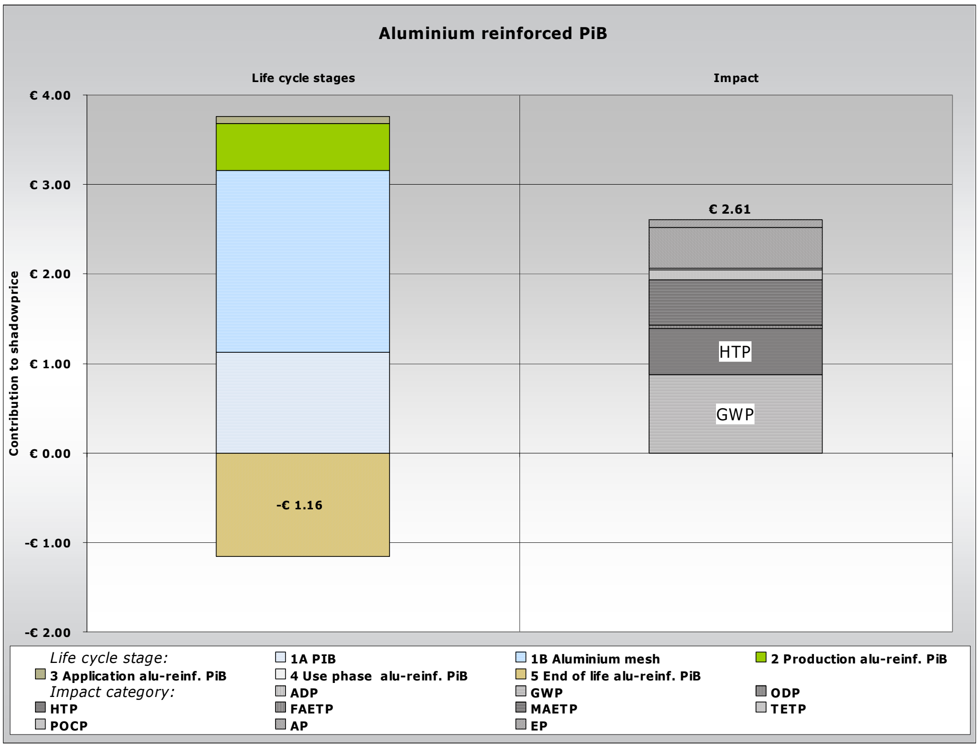

Figure 22 The environmental impact expressed in shadow costs (€) of aluminium reinforced PiB. The left bar shows the contribution of the single life cycle phases; the right bar shows the contribution of each impact category.

5.4 Aluminium reinforced SEBS modified bitumen

In the life cycle of aluminium reinforced SEBS-modified bitumen the production of the aluminium mesh is the most contributing process (see Figure 23 and Table 20). On average it accounts for nearly 60% of the environmental impact. The second most contributing process is the production of SEBS-modified bitumen. The incineration in an MSWI of the bitumen sheet at the end-of-life stage is except for TETP a clear benefit.

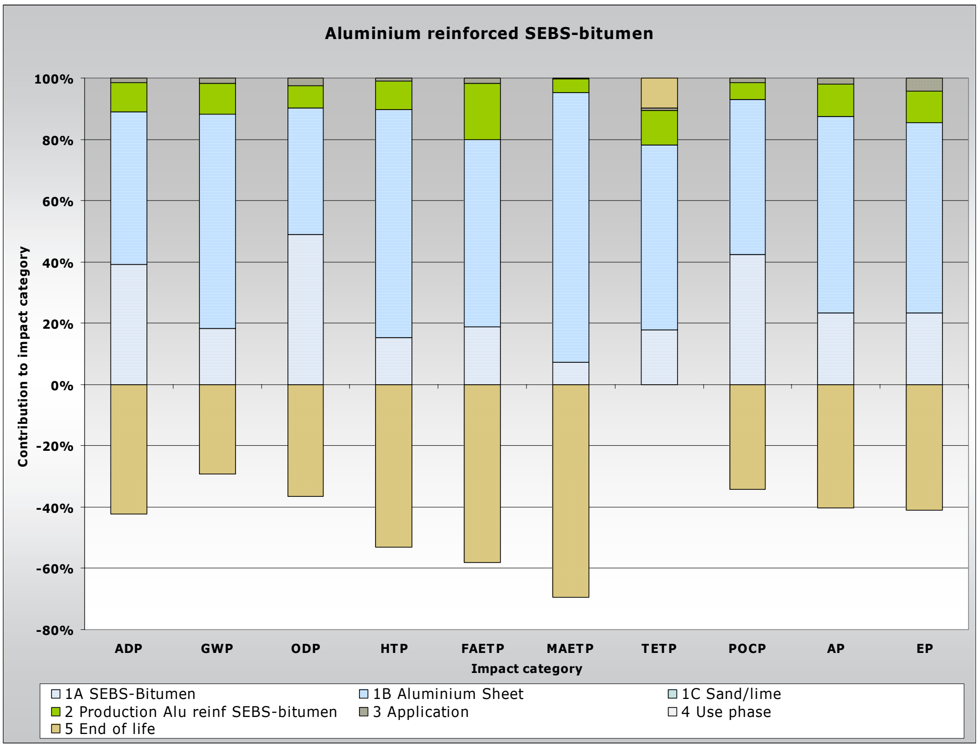

Figure 23 Environmental impacts of aluminium reinforced SEBS-modified bitumen applied as weather-proofing in the Netherlands. The impacts are relative to the total impact per category.

The use of aluminium has an important impact due to the fact that the production of primary aluminium is energy intensive. The impact of the SEBS modified bitumen relates to both the production of SEBS and that of the bitumen. The end-of-life stage shows the benefits of the incineration of the sheet in an MSWI. This is due to the generation of industrial heat and electricity from the incineration of the bitumen and the SEBS.

Table 20 Characterised environmental impacts and the environmental shadow costs for aluminium reinforced SEBS-modified bitumen sheet applied in cavity walls and wall-roof applications.

Impact	**Total**	**1A SEBS-Bitumen**	**1B Alu sheet**	**1C Sand/lime**	**2 Production SEBS bitumen sheet**	**3 Application**	**4 Use phase**	**5 End of life**
ADP kg Sb eq	2.39E-01	1.62E-01	2.06E-01	2.66E-05	3.98E-02	6.27E-03		-1.75E-01
GWP kg CO_2 eq	3.48E+01	8.98E+00	3.44E+01	3.89E-03	4.93E+00	9.05E-01		-1.44E+01
ODP kg CFC-11 eq	3.13E-06	2.42E-06	2.04E-06	5.03E-10	3.61E-07	1.20E-07		-1.81E-06
HTP kg 1,4-DB eq	1.00E+01	3.26E+00	1.59E+01	9.56E-04	1.98E+00	2.06E-01		-1.13E+01
FAETP kg 1,4-DB eq	5.09E-01	2.29E-01	7.42E-01	1.03E-04	2.22E-01	2.17E-02		-7.06E-01
MAETP kg 1,4-DB eq	7.16E+03	1.70E+03	2.06E+04	3.95E-01	1.06E+03	8.32E+01		-1.63E+04
TETP kg 1,4-DB eq	2.09E-01	3.73E-02	1.26E-01	8.32E-06	2.36E-02	1.67E-03		2.02E-02
POCP kg C_2H_4	1.93E-02	1.25E-02	1.48E-02	1.81E-06	1.64E-03	4.31E-04		-1.01E-02
AP kg SO_2 eq	1.52E-01	5.93E-02	1.63E-01	2.12E-05	2.72E-02	4.95E-03		-1.02E-01
EP kg PO_4^{3-} eq	1.36E-02	5.38E-03	1.43E-02	4.23E-06	2.39E-03	9.87E-04		-9.46E-03
Shadow costs	**€ 4.32**	**€ 1.25**	**€ 6.06**	**€ 0.00**	**€ 0.68**	**€ 0.10**	**-**	**-€ 3.78**

The shadow costs, in total €4.32 over the life cycle, also show that the production of the aluminium mesh and of the production of the SEBS-bitumen are the main contributors. The recycling of the aluminium, from the incinerated sheet, at the end-of-life is beneficial for this stage.

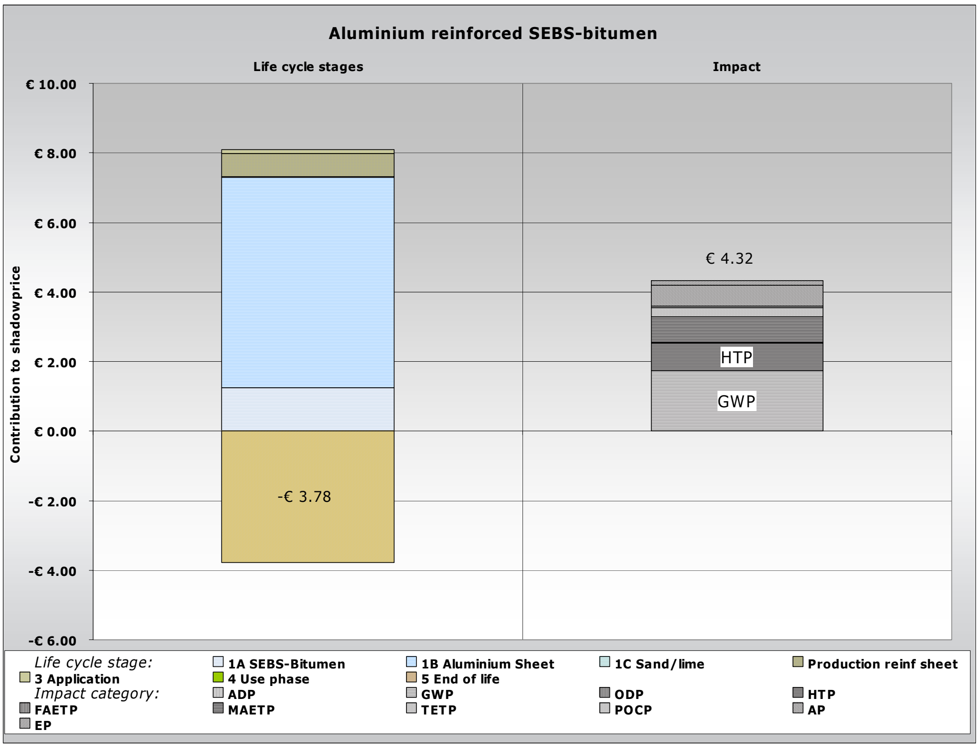

Figure 24 The environmental impact expressed in shadow costs (€) of aluminium reinforced SEBS-bitumen. The left bar shows the contribution of the single life cycle phases; the right bar shows the contribution of each impact category.

Translating the environmental impact to shadow costs (see Figure 24) shows that the total impact is mostly related to the global warming potential (GWP) and human toxicity (HTP). The production of the aluminium sheet is, again, the most contributing stage.

5.5 Aluminium reinforced EPDM

The production of EPDM is the main contributor to the environmental impact of the aluminium reinforced EPDM sheet (see Figure 25). On average it contributes to over 60% of the total impact; it is followed by the production of the aluminium mat. It is clear that the end-of-life stage is beneficial as a part of the end-of-life waste is incinerated in an MSWI, where energy from the EPDM is partly recovered and part of the aluminium mat is recovered for recycling. The recovery of energy has the most beneficial effect.

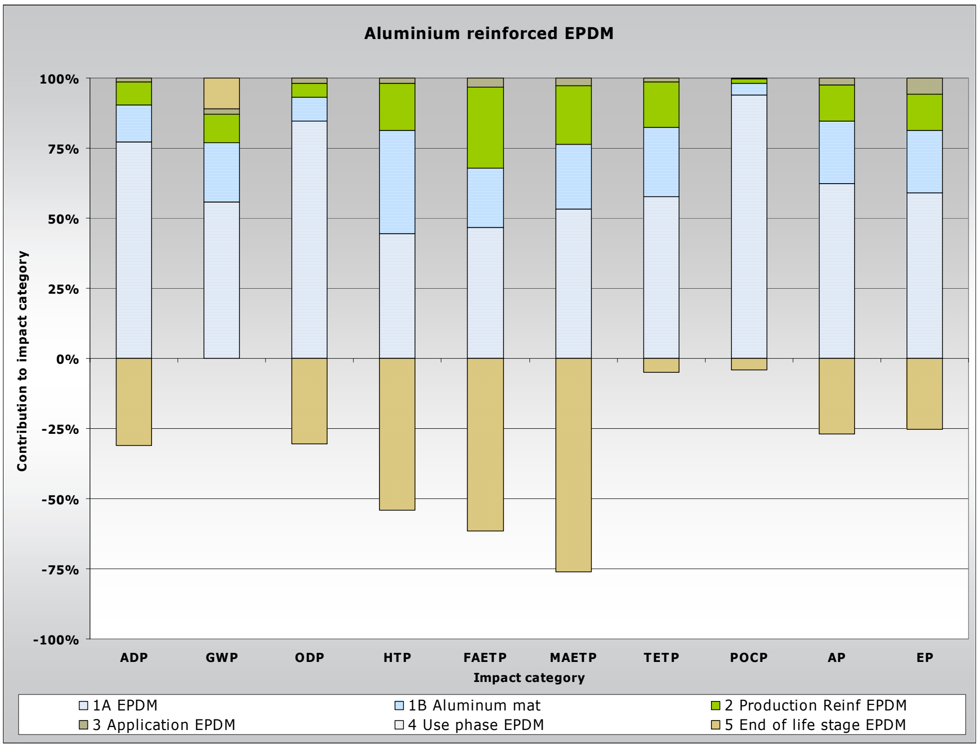

Figure 25 Environmental impacts of aluminium reinforced EPDM applied as weather-proofing in the Netherlands. The impacts are relative to the total impact per category.

The shadow costs of the reinforced EPDM sheet over the complete life cycle add up to €2.83 (see Table 21 and Figure 26).

Table 21 Characterised environmental impacts and the environmental shadow costs for aluminium reinforced EPDM.

Impact	Total	1A EPDM (kg)	1B Aluminium mat	2 Production Reinf EPDM	3 Application EPDM	4 Use phase EPDM	5 End of life stage EPDM
ADP kg Sb eq	2.30E-01	2.59E-01	4.37E-02	2.78E-02	4.66E-03		-1.04E-01
GWP kg CO_2 eq	3.39E+01	1.89E+01	7.25E+00	3.44E+00	6.72E-01		3.69E+00
ODP kg CFC-11 eq	3.45E-06	4.21E-06	4.22E-07	2.48E-07	8.93E-08		-1.52E-06
HTP kg 1,4-DB eq	3.81E+00	3.71E+00	3.06E+00	1.39E+00	1.53E-01		-4.50E+00
FAETP kg 1,4-DB eq	2.74E-01	3.33E-01	1.50E-01	2.06E-01	2.36E-02		-4.38E-01
MAETP kg 1,4-DB eq	4.96E+02	1.10E+03	4.76E+02	4.35E+02	5.47E+01		-1.57E+03
TETP kg 1,4-DB eq	1.05E-01	6.38E-02	2.75E-02	1.80E-02	1.45E-03		-5.53E-03
POCP kg C_2H_4	5.58E-02	5.46E-02	2.53E-03	8.62E-04	1.84E-04		-2.42E-03
AP kg SO_2 eq	1.08E-01	9.18E-02	3.27E-02	1.90E-02	3.68E-03		-3.96E-02
EP kg PO_4^{3-} eq	9.48E-03	7.48E-03	2.83E-03	1.64E-03	7.33E-04		-3.20E-03
Shadow costs	**€ 2.83**	**€ 1.99**	**€ 0.86**	**€ 0.45**	**€ 0.08**	**-**	**-€ 0.55**

The production of EPDM also has the largest contribution to the shadow costs, followed by the production of the aluminium mat (see Figure 26). The end-of-life stage shows a beneficial effect. The most contributing impact categories are global warming, with 60% contribution, and acidification, which contributes 15%.

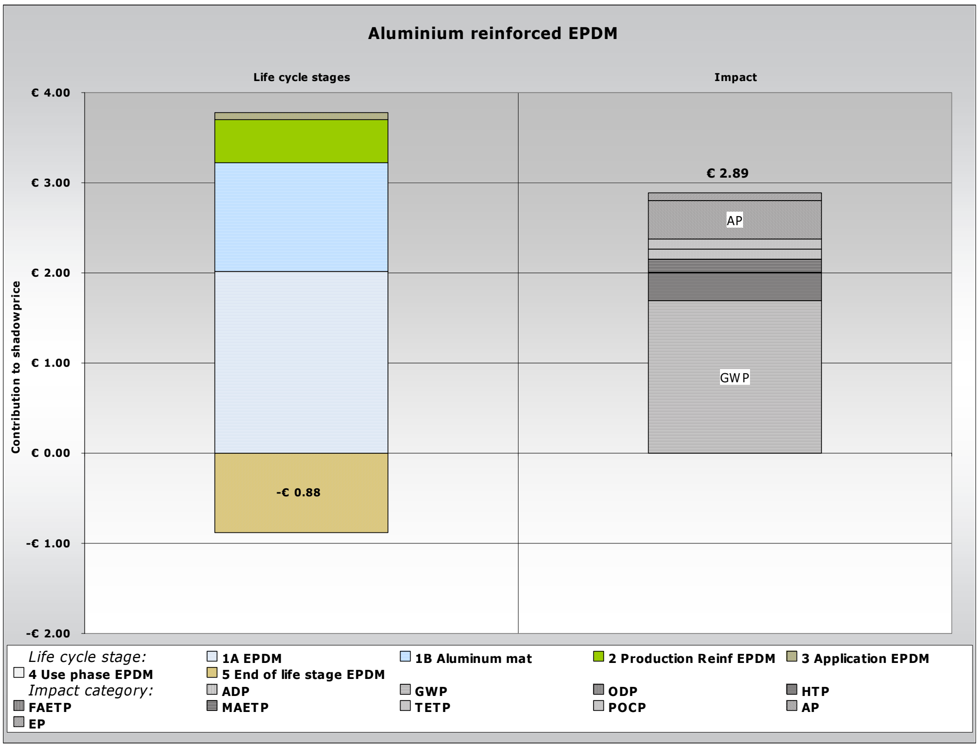

Figure 26 The environmental impact expressed in shadow costs (€) of aluminium reinforced EPDM. The left bar shows the contribution of the single life cycle phases; the right bar shows the contribution of each impact category.

5.6 PVC

The environmental profile of PVC used as a weather-proofing material (see Figure 27) shows a remarkable feature. For the impact ozone depletion (ODP) the negative bar of the end-of-life stage is larger than the impact of the other stages for this category. This is most likely due to an inconsistency in the database with the LCI data for the used processes. For some impact categories (GWP and TEP) the end-of-life stage has no longer net benefits, but has an impact.

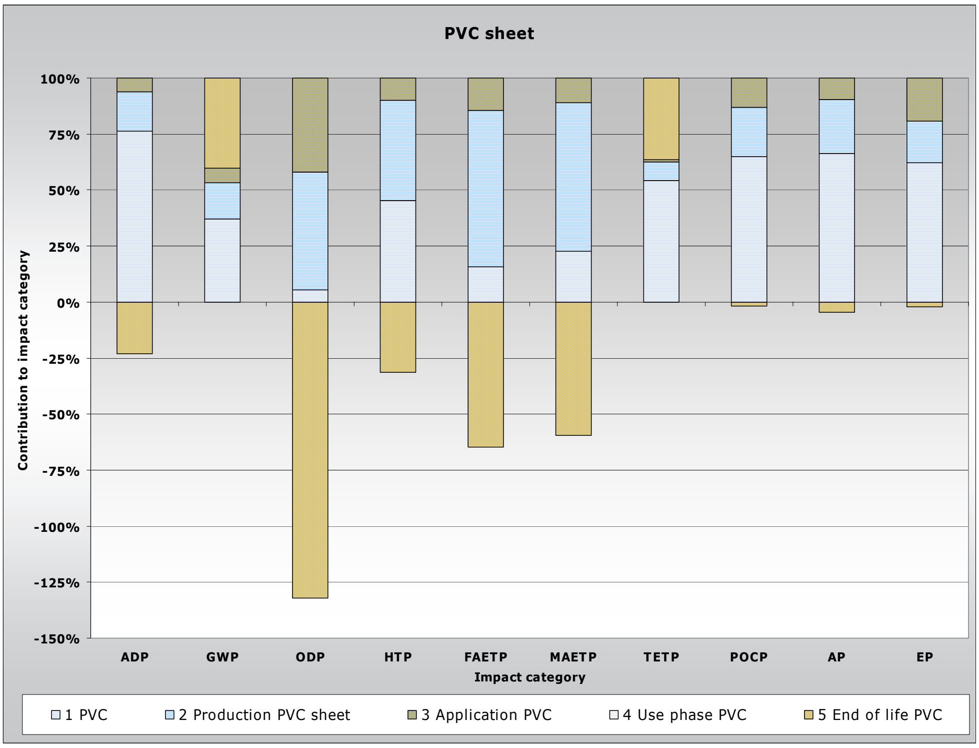

Figure 27 Environmental impacts of PVC sheet applied as weather-proofing in the Netherlands. The impacts are relative to the total impact per category.

The production of the PVC itself and the production of the sheet are other processes that dominate the environmental profile (see also Table 22).

When translating the environmental impact to shadow costs it shows (see Figure 28 and Table 22) that the end-of-life stage has positive costs, i.e. an environmental impact. This is due to the relatively large contribution of GWP and TETP in this case. For these impact categories the end-of-life stage has no net benefit.

Impact	**Total**	**1 PVC**	**2 Production PVC sheet**	**3 Application PVC**	**4 Use phase PVC**	**5 End of life PVC**
ADP kg Sb eq	1.55E-01	1.54E-01	3.54E-02	1.21E-02		-4.62E-02
GWP kg CO_2 eq	2.66E+01	9.83E+00	4.32E+00	1.75E+00		1.07E+01
ODP kg CFC-11 eq	-1.77E-07	2.93E-08	2.90E-07	2.32E-07		-7.29E-07
HTP kg 1,4-DB eq	2.78E+00	1.84E+00	1.81E+00	3.98E-01		-1.27E+00
FAETP kg 1,4-DB eq	1.03E-01	4.60E-02	2.04E-01	4.19E-02		-1.89E-01
MAETP kg 1,4-DB eq	5.99E+02	3.33E+02	9.87E+02	1.61E+02		-8.82E+02
TETP kg 1,4-DB eq	2.68E-01	1.45E-01	2.20E-02	3.23E-03		9.74E-02
POCP kg C_2H_4	6.19E-03	4.10E-03	1.37E-03	8.33E-04		-1.14E-04
AP kg SO_2 eq	9.52E-02	6.61E-02	2.39E-02	9.56E-03		-4.39E-03
EP kg PO_4^{3-} eq	9.69E-03	6.18E-03	1.83E-03	1.91E-03		-2.27E-04
Shadow costs	**€ 2.45**	**€ 1.19**	**€ 0.61**	**€ 0.20**	**-**	**€ 0.45**

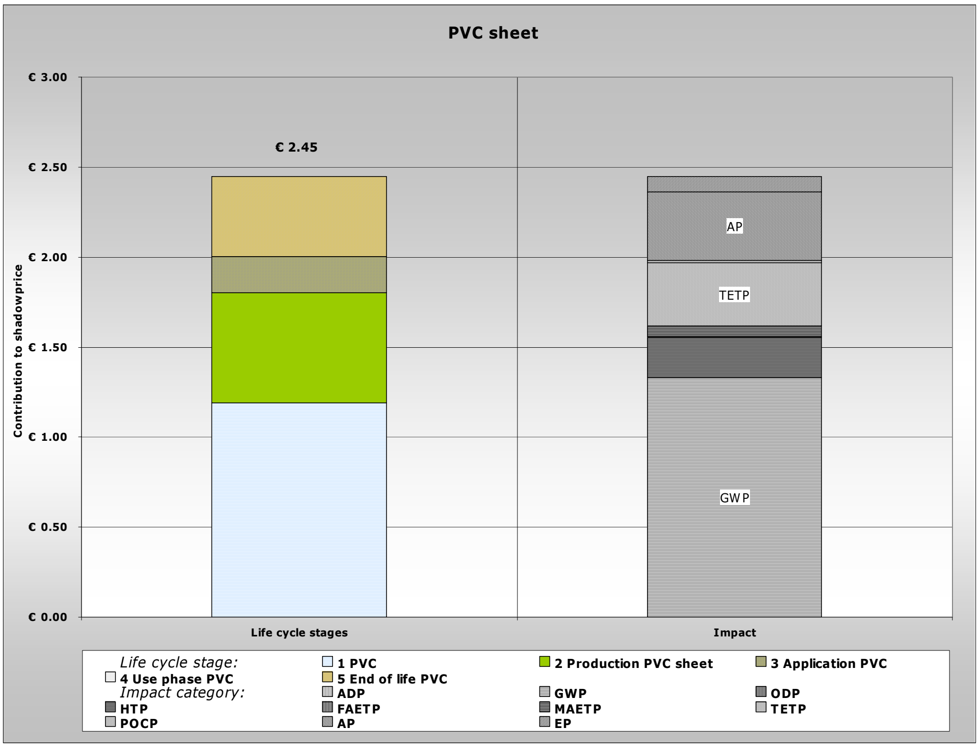

Figure 28 *The environmental impact expressed in shadow costs (€) of PVC sheet. The left bar shows the contribution of the single life cycle phases; the right bar shows the contribution of each impact category.*

5.7 Glass fibre reinforced polyester

The production of the polyester resin and accelerator is by far the most contributing process to the environmental profile (Figure 29). On average it accounts for over 80% of the total impact. The second most contributing process is that of the fibre glass production, while the incineration as part of the end-of-life stage of the reinforced polyester shows for most categories a slightly beneficial effect.

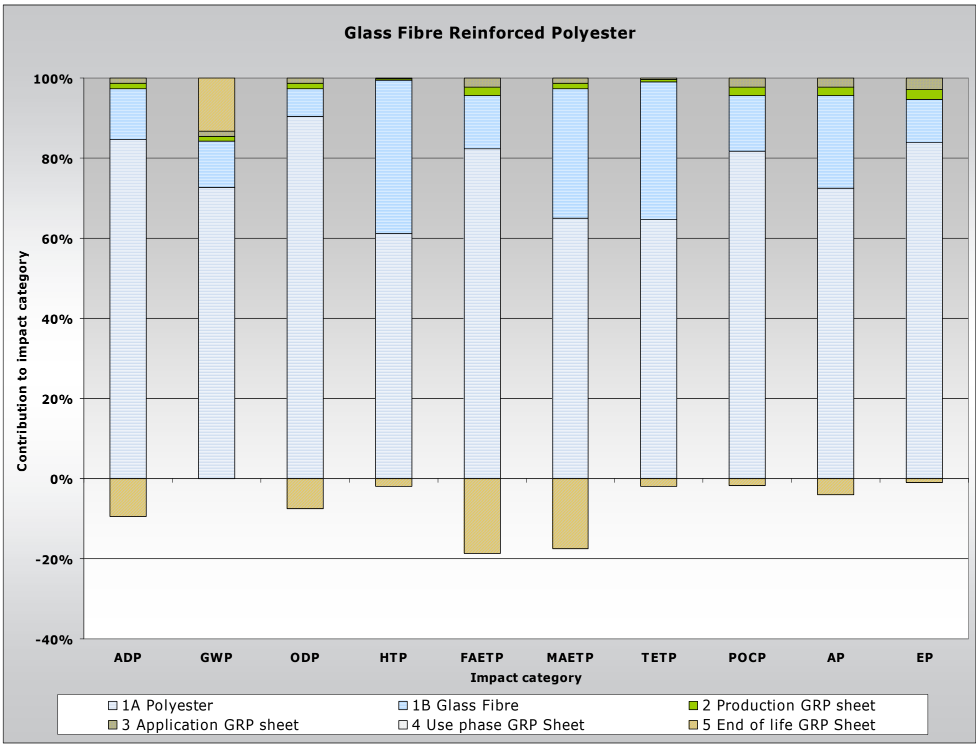

Figure 29 Environmental impacts of glass fibre reinforced polyester (GRP) sheet applied as weather-proofing in the Netherlands. The impacts are relative to the total impact per category.

Table 23 Characterised environmental impacts and the environmental shadow costs for aluminium reinforced.

Impact	**Total**	**1A Polyester bulk**	**1B Glass Fibre**	**2 Production GRP sheet**	**3 Application GRP sheet**	**4 Use phase GRP Sheet**	**5 End of life GRP Sheet**
ADP kg Sb eq	2.46E-01	2.29E-01	3.47E-02	3.48E-03	3.85E-03		-2.53E-02
GWP kg CO_2 eq	4.18E+01	3.04E+01	4.77E+00	5.02E-01	5.55E-01		5.56E+00
ODP kg CFC-11 eq	4.87E-06	4.76E-06	3.62E-07	6.67E-08	7.38E-08		-3.98E-07
HTP kg 1,4-DB eq	4.37E+01	2.72E+01	1.71E+01	1.14E-01	1.26E-01		-8.33E-01
FAETP kg 1,4-DB eq	4.64E-01	4.69E-01	7.59E-02	1.20E-02	1.33E-02		-1.06E-01
MAETP kg 1,4-DB eq	3.04E+03	2.39E+03	1.19E+03	4.61E+01	5.10E+01		-6.42E+02
TETP kg 1,4-DB eq	2.17E-01	1.43E-01	7.61E-02	9.28E-04	1.03E-03		-4.12E-03
POCP kg C_2H_4	1.11E-02	9.22E-03	1.56E-03	2.39E-04	2.65E-04		-1.89E-04
AP kg SO_2 eq	1.27E-01	9.59E-02	3.05E-02	2.75E-03	3.04E-03		-5.32E-03
EP kg PO_4^{3-} eq	2.12E-02	1.80E-02	2.29E-03	5.48E-04	6.05E-04		-1.86E-04
Shadow costs	**€ 6.91**	**€ 4.71**	**€ 1.97**	**€ 0.06**	**€ 0.06**	**-**	**€ 0.11**

The shadow costs, €6.91 in total, of the glass fibre reinforced polyester are dominated by the production of polyester, followed by the production of glass fibre (see Table 23 and Figure 30). The end-of-life stage also shows an impact with shadow costs of €0.11.

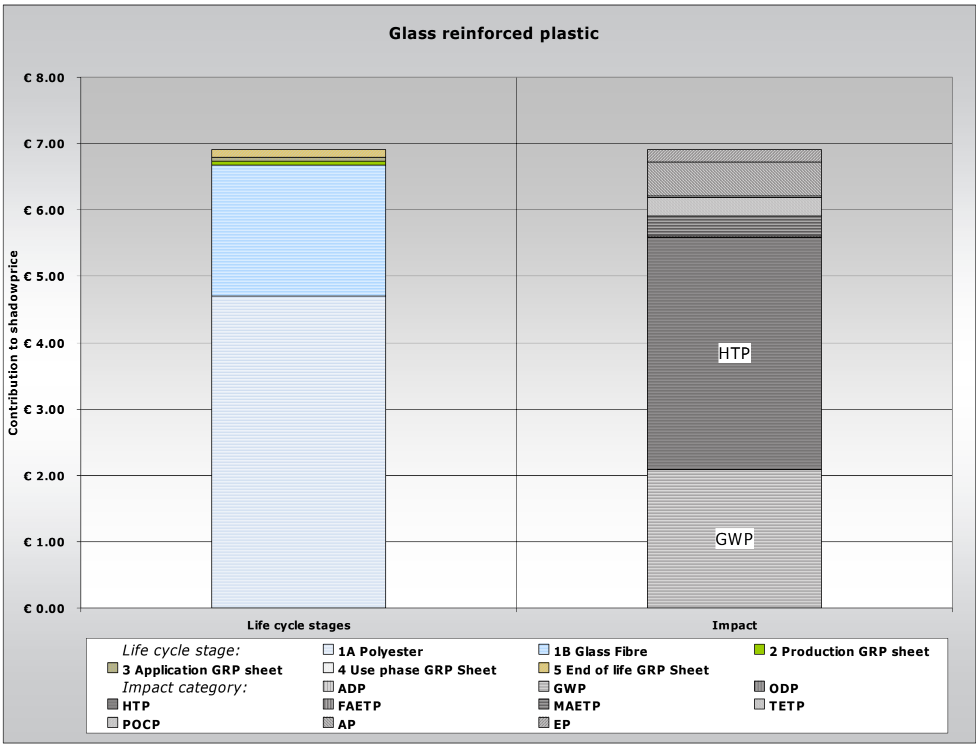

Figure 30 The environmental impact expressed in shadow costs (€) of glass fibre reinforced sheet. The left bar shows the contribution of the single life cycle phases; the right bar shows the contribution of each impact category.

The impact categories that mostly determine the shadow costs are HTP and GWP. For HTP the emission of arsenic at the glass fibre production and the emission of propylene oxide at the polyester resin production are the most contributing substances.

5.8 Comparison of alternative materials

The comparison of the several products shall be based on the shadow costs as comparison per impact category yields non-transparent results. Due to the uncertainties and variability in the input data and uncertainty in the method itself differences smaller than 20% are seen as insignificant.

5.8.1 Comparison for cavity wall application

As lead has a relatively small impact related to the production and use of materials its environmental performance is with a shadow cost of €1.47 the best material for cavity wall applications (see Figure 31). The total shadow cost of the aluminium reinforced SEBS-modified bitumen is at €4.32 the highest of the four compared materials.

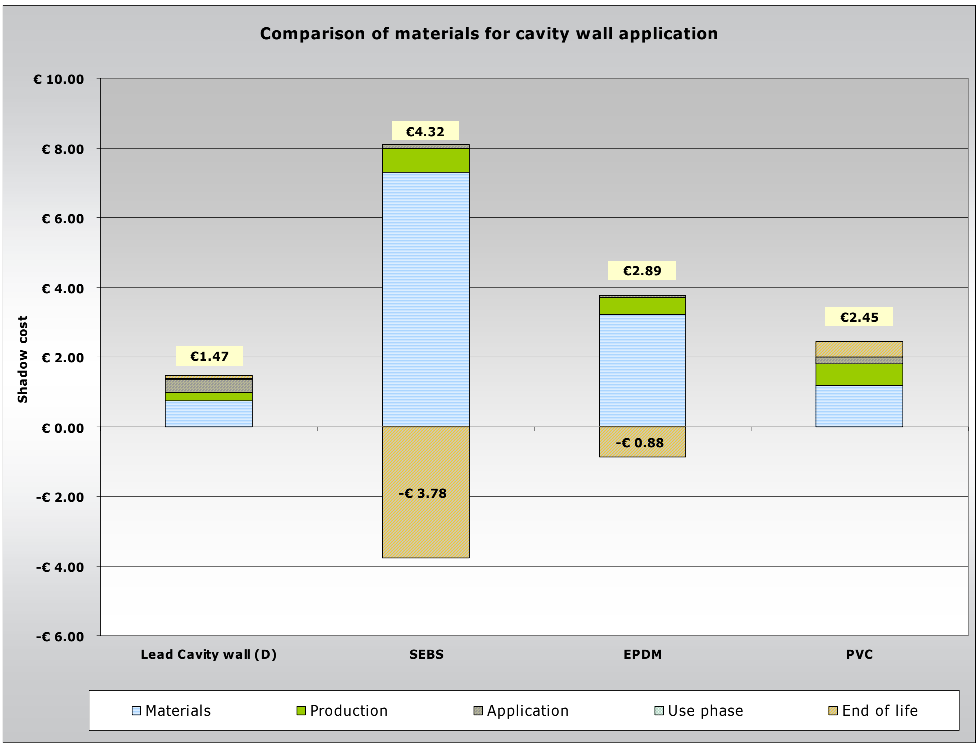

Figure 31 Comparison of the shadow costs of the three materials applied for cavity walls. For lead sheet the German situation is used. The net shadow costs are given above each bar.

5.8.2 Comparison for wall/roof applications

Four materials are used as flashings in wall/roof situations:
- lead sheet;
- aluminium reinforced PiB sheet;
- aluminium reinforced SEBS-modified bitumen.

The lead flashing performs, with a shadow cost of €1.94, clearly (see Figure 32) better than the aluminium reinforced SEBS-modified bitumen, which has a shadow cost of €4.32.

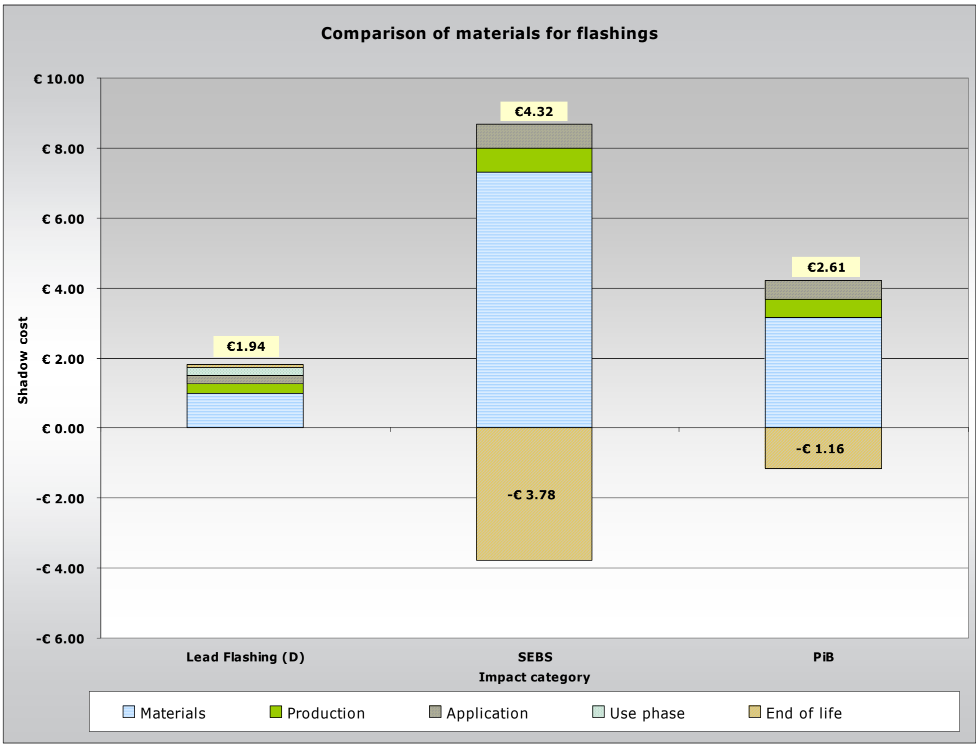

Figure 32 Comparison of the shadow costs of the four materials applied for wall/roof situations. The net shadow costs are given above each bar.

5.8.3 Comparison gutter applications

Two materials are applied in valley gutters: lead sheet and glass fibre reinforced polyester (GRP). The latter has a high shadow cost of €6.91 for the full life cycle (see Figure 33). The lead sheet, for which the exposure data of flashing have been used, has only a shadow cost of €1.79.

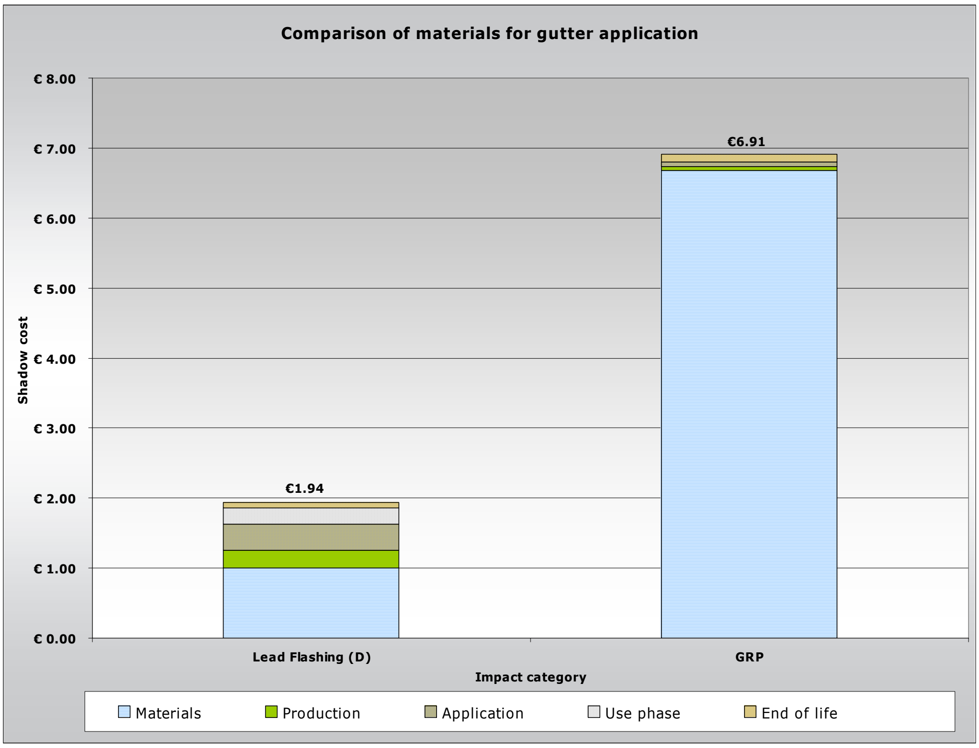

Figure 33 Comparison of the shadow costs of the two materials applied for gutter applications. The net shadow costs are given above each bar.

6. Sensitivity analyses

6.1 Introduction

For an LCA a check for the reliability of the final results is made by means of a sensitivity analysis. The final results and related conclusions are checked by determining whether they are affected by uncertainties in the data, allocation methods or calculation of category indicator results, etc.

In this study the results may be affected by uncertainties in assumptions made to describe the studied product systems in detail. These uncertainties should especially be investigated for those parts of the product system that have a strong impact on the LCIA results.

6.2 Subjects for sensitivity analysis

Based on an evaluation of the study a number of subjects for the sensitivity analysis have been chosen. They are shown in Table 24.

Table 24 Subjects for sensitivity analyses.

System	Topic	Base	Sensitivity
Aluminium reinforced SEBS-modified bitumen	Production of SEBS-bitumen	18% synthetic rubber and 82% sealing bitumen	10% synthetic rubber and 90% sealing bitumen
Glass fibre reinforced polyester	Production of sheet	Hand lay-up	Injection moulding
Aluminium containing products	End-of-life: recovery MSWI	60% recovery	30% and 90% recovery

6.3 SEBS-bitumen ratio

In the base case a ratio of 18% SEBS and 82% bitumen has been used. As there is uncertainty in the exact ratio of SEBS to bitumen the effect a changing this ratio has been studied. The analysis showed (see Figure 34) that a ratio of 10% SEBS to 90% bitumen only slightly reduced the environmental impact to 97% of the base case. The main reduction is found for the impact of the production of the raw materials.

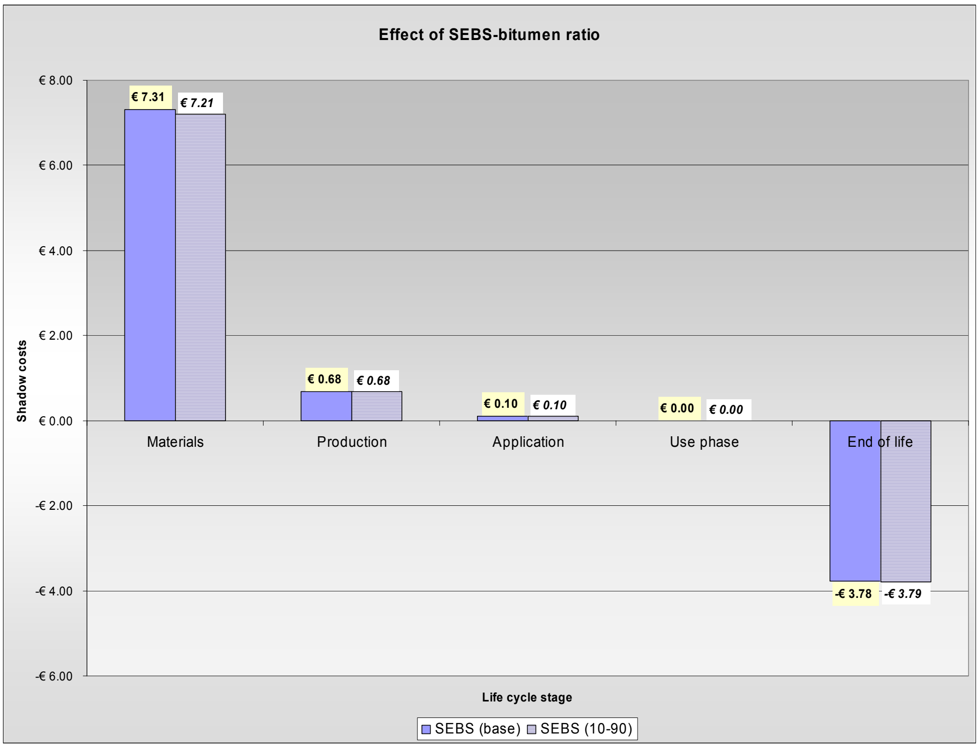

Figure 34 Impact of a changed SEBS to bitumen ratio for the aluminium reinforced SEBS-modified bitumen sheet. In the base case a ratio of 18:82 has been used; the sensitivity analysis used a ratio of 10:90.

The change in the SEBS:bitumen ratio does not affect its position in the comparison with the other products in cavity wall and flashing applications.

6.4 Production process for the glass fibre reinforced polyester

In the base case the GRP sheet is formed by hand lay up. As a production process that uses injection moulding is also a possibility and as it is expected that this will lead to a change in the environmental impact of this sheet a sensitivity analysis has been performed.

Using injection moulding[1] as the production process increases the environmental impact of the glass fibre reinforced polyester sheet to 111% of the base case value (see Figure 35). The use of electricity in the moulding process is the main cause of the increase.

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[1] The process was based on the injection moulding of glass fibre reinforced polyamide from the Ecoinvent database [14].

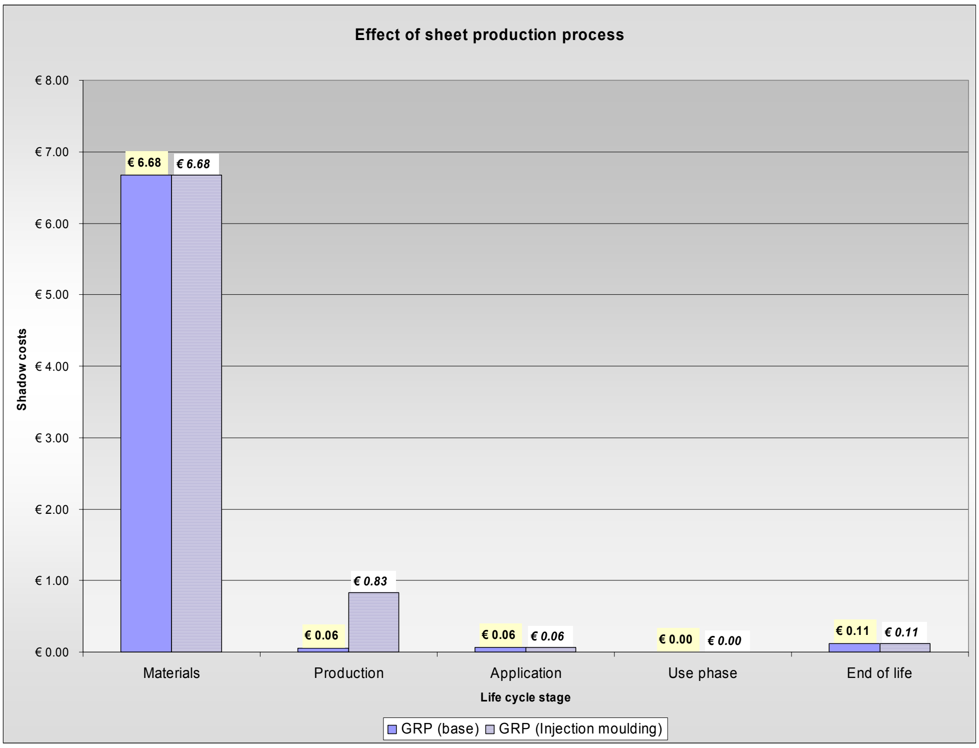

Figure 35 Impact of changing the production process for the GRP sheet from hand lay up in the base case to injection moulding.

The change in the production process does not influence the position of the GRP sheet compared to lead sheet used in valley gutter applications.

6.5 Recovery percentage of aluminium from incinerated product wastes

A number of the products uses aluminium for reinforcement of the sheet (SEBS-modified bitumen, PiB and EPDM sheet). In the base case a recovery percentage of 60% has been assumed based on the incineration model of the VLCA [20]. As this recovery greatly reduces the environmental impact and as the rate of recovery may vary within Europe a sensitivity analysis has been conducted.

The results of the sensitivity analysis (see Figure 36 and Table 25) show that especially the aluminium reinforced SEBS-modified bitumen is sensitive. A decrease in recovery rate from 60% to 30% results in an increase in environmental impact to 140% of the base case. The increase in recovery from 60% to 90% gives rise to a decrease in environmental impact of 56% of the base case value. This product has the highest sensitivity as it uses relatively the largest amount of aluminium (37% of the mass).

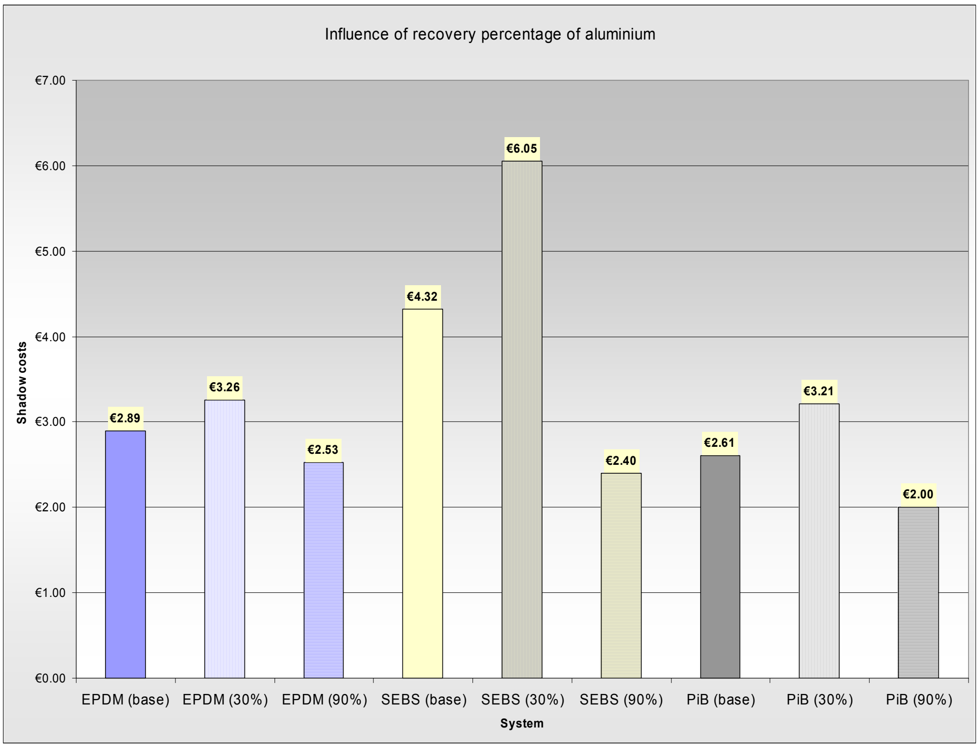

Figure 36 *Impact of changing the recovery percentage of aluminium from the incinerated product wastes from 60% in the base case to 30% and 90% in the sensitivity analysis.*

Only in case the aluminium recovery percentage is 90% the PiB sheet becomes comparable with the lead sheet (German situation) for flashing applications. However, a recovery percentage of 90% which also includes the loss in value of the aluminium compared to primary aluminium is an absolute maximum. It will thus not change the position of the PiB sheet compared to the lead sheet (see section 5.8.2 Comparison for wall/roof applications) in practice.

Table 25 *Effect of changing the percentage of aluminium recovery at the MSWI from 60% in the base case to 30% and 90% on the shadow costs of the aluminium reinforced sheets.*

Sheet system	Alu-reinforced EPDM	Alu-reinforced SEBS modified bitumen	Alu-reinforced PiB
Base case	€2.89 (100%)	€4.32 (100%)	€2.61 (100%)
30% recovery	€3.26 (113%)	€6.05 (140%)	€3.21 (123%)
90% recovery	€2.53 (87%)	€2.40 (56%)	€2.00 (77%)

7. Conclusions

– ***Application of HC50 based characterisation factors***

When the eco-toxicity related characterisation factor of a substance is based on the median of multi-species HC50 values instead of on the PNEC values a more reliable result will be generated. In this study the characterisation factors of the top ten contributing substances in a pre-assessment (PNEC based) were adjusted for HC50 or LC50 data. For most substances this leads to a marked reduction of the characterisation factors for all impact categories except for those of the terrestrial ecotoxicity (TETP).

The reduction of the environmental impact –for TETP an increase was seen– was most pronounced for the products other then lead sheet.

The use of shadow prices is seen as a robust and realistic method to translate the results of the ten baseline impact categories into a single value. The method is intended to be applied with the CML2 method. When using the adjusted characterisation factors the shadow prices should ideally be recalculated as changes may occur. *(pm a sensitivity analysis which used the unadjusted factors showed that the relative position of lead sheet compared to the alternatives did not change)*

– ***Environmental impact of products***

In the life cycle of ***lead sheet***, applied as a weather-proofing material, the production of primary lead, needed to replenish the losses from the product's life cycle due to incomplete recovery of post-consumer lead, is the most contributing process. The recovery of lead at the end-of-life stage is thus an important factor affecting the environmental impact.
The use stage, where run-off emissions of lead to the environment occur, is only of significance for lead sheet almost fully exposed to the environment as for flashings. In this case the run-off emissions dominate the terrestrial ecotoxicity.

The life cycle of ***aluminium reinforced PiB*** is dominated by the production of PiB and the aluminium reinforcement. The recuperation and subsequent recycling of the aluminium from the application and the incineration of the end-of-life waste reduce the environmental impact for most impact categories.

The production of the base materials SEBS, bitumen and that of the aluminium mesh are the most contributing processes in the life cycle of ***aluminium reinforced SEBS-modified bitumen***. Again the recycling of the aluminium mesh after incineration is beneficial for the environmental impact of this product

The same important processes are seen for another reinforced product ***aluminium reinforced EPDM***.

The weather-proofing product based on a ***PVC*** sheet shows that the production of PVC and the production of the sheet are the most contributing processes. The incineration at the end of life is beneficial for most, but not all, impact categories.

The production of the polyester resin is the most contributing process in the environmental profile of ***glass fibre reinforced polyester***. The production of the glass fibre is the second most contributing process. The incineration of the product at the end-of-life stage shows for most impact categories only a small benefit; the marine aquatic eco-toxicity is an exception as it shows a strong beneficial effect.

- ***Comparison of products***

The comparison of lead sheet with the other weather-proofing products is done per function (cavity wall, wall/roof, valley gutter) and is based on the shadow prices method.

For ***cavity wall*** applications the use of lead sheet has the smallest impact with a shadow cost of €1.47 (German situation). Aluminium reinforced SEBS-modified bitumen has, with €4.32, the highest impact of all three compared materials. Aluminium reinforced EPDM and PVC have intermediate scores.

The materials used for flashings for ***wall/roof*** situations are:
- lead sheet;
- aluminium reinforced PiB sheet;
- aluminium reinforced SEBS-modified bitumen.

The lead flashing performs, with a shadow cost of €1.94 (German situation) clearly better than the aluminium reinforced SEBS-modified bitumen, which has a shadow cost of €4.32. The lead sheet performs, when taking differences below 20% as non-significant, equal compared with the environmental performance of the PiB sheet.

For the materials that are applied in ***valley gutters***, lead sheet has the best performance with a shadow cost of €1.94. The alternative glass fibre reinforced polyester has a shadow cost of €6.91 per full life cycle.

The results of the sensitivity analyses have not lead to changes in the conclusions for the comparison of the products.

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9. Authentication

Name and address of the principal:
European Lead Sheet Industry Association (ELSIA)

Names and functions of the cooperators:
Tom N. Ligthart

Names and establishments to which part of the research was put out to contract:

Date upon which, or period in which, the research took place:

Signature:	Approved by:
A.M.M. Ansems project leader	H.S. Buijtenhek head of department

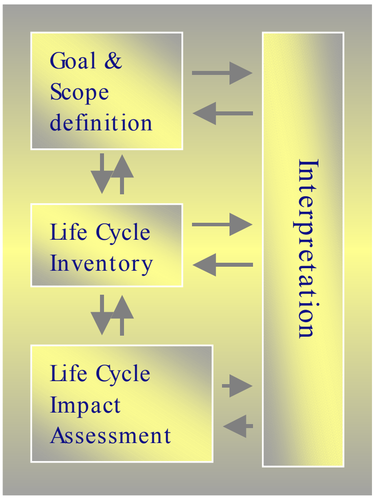
Appendix A Abbreviations

Abbreviation	Meaning
ADP	Abiotic Resource Depletion Potential
Alu	Aluminium
AP	Acidification Potential
CML	Centre for Environmental Sciences Leiden
DEHP	Di-2-ethylhexyl phthalate
EP	Eutrophication Potential
EPDM	Ethylene Propylene Diene Monomer synthetic rubber
FAETP	Fresh water Aquatic Eco-toxicity Potential
GRP	Glass fibre reinforced polyester
GWP	Global Warming Potential
HC50	Hazardous Concentration at 50% calculated as the geometric mean of LC50 (lethal concentration for 50% of the individuals) or EC50 (environmental concentration)
HTP	Human Toxicity Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MAETP	Marine aquatic Eco-toxicity Potential
MSWI	Municipal Solid Waste Incinerator
NOEC	No Observed Effect Concentration
ODP	Ozone Depletion Potential
PiB	Polyisobutylene
PNEC	Predicted No Effect Concentration
POCP	Photochemical Ozone Creation Potential
PVC	Polyvinyl chloride
SEBS	Styrene-ethylene-butadiene-styrene (polymer)
TETP	Terrestrial Eco-toxicity Potential

Appendix B Life cycle assessment

Introduction

The method of environmental Life Cycle Assessment (LCA) is seen as a suitable instrument for the evaluation of the environmental impacts of a product or an activity through its entire life cycle.



LCA is a systematic way to evaluate the environmental impacts of product system or activities by following a “cradle-to-grave” approach. The product system consists of a set of activities (processes), all focused on the fulfilment of the required function. These activities can be executed at different places and in different time periods. Therefore it is not possible to produce results, which refer to “real” environmental effects, since this requires specific locations and specific periods.
The result of a life cycle analysis is expressed in terms of “potential” effects. These potential effects are indicators for the real effects on local, regional and global level.

LCA structure

The LCA methodology is structured along a framework with four main steps or phases (ISO 14040):

1. Goal and scope definition;
2. Inventory analysis;
3. Impact assessment;
4. Interpretation.

These phases are part of an iterative process; the main flow is according to the above sequence.

1 Goal and scope definition

This deals with the clear and unambiguous formulation of the research question and the intended application of the answer that the LCA study is supposed to provide. Important elements of the goal and scope definition are the choice of the functional unit, the selection of product alternatives to be analysed, and the definition of the reference flows for each of the alternative systems.

2 Inventory analysis

The phase is concerned with the construction of the product systems. These systems are composed of unit processes, like industrial production, waste treatment, transport and so on.

The system boundaries and flow charts of linked unit processes are drawn for each alternative product system, and quantitative input and output data for each unit process are collected, i.e. raw materials and energy use figures, as well as emissions and waste amounts. Furthermore qualitative data for representativeness, data quality etc. are collected during this phase. For those unit processes that are multifunctional, i.e. that produce more than one product; an allocation step is made: all input and output data of the unit process is allocated to each of the products, according to chosen rule (e.g. on basis of mass ratio or economic value). A final step of the inventory analysis is the aggregation of the emissions of chemicals and the extractions of natural resources over the entire product system, in such a way that a quantitative match with the system's reference flow is achieved. The result of the inventory analysis is often a long list with entries, such as carbon dioxide, nitrogen oxides, chloromethane and mercury.

3 Impact assessment

This phase aims to convert and aggregate the results of the inventory analysis into environmentally relevant items. In particular, we mention here the step of characterisation, in which the inventory results are transformed into a number of contributions to environmental impact categories, such as global warming, acidification, and ecotoxicity. Optionally the characterisation results may be normalised in order to relate the results to a reference value, such as the annual global or European extent of each impacts. Finally, a weighting step may be performed, in which priority weights are assigned to the characterisation or normalisation results, and which may result into one final score for each alternative product system.

Table B1 shows an example calculation (characterisation only).

Table B1 Example of impact assessment (characterised effect scores).

Substance	**Quantity**	**Characterisation factors (kg eq/kg)**			
	(kg)	**GWP_{100}**	**POCP**	**HTP**	**AP**
CO_2	220	1			
methane	3	11	0.007		
NO_x	8			0.78	0.7
N_2O	8	270			
benzene	5		0.189	3.9	
C_xH_y	5		0.377		
scores		220*1 + 3*11 + 8*270 = **2413 kg CO_2 eq**	3*0.007 + 5*0.189 + 5*0.377 = **2.851 kg C_2H_2 eq**	8*0.78 + 5*3.9 = **25.74 kg DCB eq**	8*0.7 = **5.6 kg SO_2 eq**

Appendix C Life Cycle Inventory data

In this appendix the LCI data or data sources are shown for each of the studied materials and processes.

Common

Transport processes have, as far as they have not been included in the LCI data of materials, been based on the Ecoinvent database [14].

Data for materials and processes have been, if no specific data are available, primarily selected from the Ecoinvent database [14]. In case this database yields no useful result the data have been selected form other recent databases like that from ETH [21] or APME [22].

Lead sheet

Phase	Material or process	Source
Production raw materials	Secondary lead	[1], updated for energy sources.
	Primary lead	[14], Lead at regional store
Production of weather-proofing sheets		[1], updated for energy sources.
Use	Distribution of lead run-off	[1], updated for new run-off rate.
End-of-life	Recycling	Only transports to recycler included.
	Lead in landfill	TNO waste model [20]
	Lead in MSWI	TNO waste model [20]

Aluminium reinforced PiB

Phase	Material or process	Source
Production raw materials	PiB (polyisobutylene)	[1], updated for energy sources.
	Aluminium	[14], Aluminium production mix
	Alu sheet	[14], Aluminium sheet processing
Production of weather-proofing sheets		No data
Use		No impact assumed
End-of-life	Alu reinforced PiB in landfill	Based on TNO waste model [20]
	Alu reinforced PiB in MSWI	Based on TNO waste model [20]

Aluminium reinforced SEBS modified bitumen

Phase	Material or process	Source
Production raw materials	SEBS	[14], Synthetic rubber
	Bitumen	[14], Bitumen, sealing
	Aluminium	[14], Aluminium production mix
	Alu sheet	[14], Aluminium sheet processing
Production of weather-proofing sheets		No data
Use		No impact assumed
End-of-life	Alu reinforced SEBS bitumen in landfill	Based on TNO waste model [20]
	Alu reinforced SEBS bitumen in MSWI	Based on TNO waste model [20]

Aluminium reinforced EPDM

Phase	Material or process	Source
Production raw materials	EPDM	[14], Synthetic rubber
	Aluminium	[14], Aluminium production mix
	Alu sheet	[14], Aluminium sheet processing
Production of weather-proofing sheets		No data
Use		No impact assumed
End-of-life	Alu reinforced EPDM in landfill	Based on TNO waste model [20]
	Alu reinforced EPDM in MSWI	Based on TNO waste model [20]

PVC

Phase	Material or process	Source
Production raw materials	PVC	[14], PVC, bulk polymerised
	DEHP	[19]
	ZnO	[14], based on zinc for coating with 80.3% zinc
	limestone	[14], milled limestone
Production of weather-proofing sheets		No data
Use		No impact assumed
End-of-life	PVC in landfill	Based on TNO waste model [20]
	PVC in MSWI	Based on TNO waste model [20]

Glass fibre reinforced polyester

Phase	Material or process	Source
Production raw materials	Polyester	[14], Polyester resin, unsaturated (97.5%) and 2.5% organic chemicals as additives
	Glass fibre	[14], glass fibre
Production of weather-proofing sheets		No data
Use		No impact assumed
End-of-life	Glass fibre reinforced polyester in landfill	Based on TNO waste model [20]
	Glass fibre reinforced polyester in MSWI	Based on TNO waste model [20]

Appendix D HC50 values of top ten substances

Calculated HC50 values of the reference substance 1,4-dichlorobenzene and the 'top ten' substances.

	HC50 Geometric mean			
Substance	**HTP [mg.kg^{-1}]**	**FAETP [mg.l^{-1}]**	**MAETP [mg.l^{-1}]**	**TETP [mg.kg^{-1}]**
1,4-dichlorobenzene	1.99E+03	3.26E+00	2.26E+01	1.57E+02
Copper, ion		2.43E-01		
Nickel, ion		1.85E+00		
Vanadium, ion		8.73E+00		
PAH, polycyclic aromatic hydrocarbons	2.97E+02			
Lead	5.96E+02			
Hydrogen fluoride			3.22E+02	
Beryllium			5.58E+00	
Vanadium, ion			6.07E+00	
Mercury				?
Chromium VI				?