Sustainability evaluationof high value-added applications

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Sustainability evaluation of high value-added products

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Content

Summary

The overview of published sustainability studies on high added-value products from biobased feedstock shows that the move to biobased products is not by definition a win for the environment. A case by case analysis is up till now necessary to make a sustainable choice between a biobased or a non-biobased product.

Most sustainability studies of products are based on an LCA approach. In many cases a biobased alternative scores better on one environmental impact category, but worse on another. Therefore LCAs cannot at this time provide a definitive answer as to the preferability of biobased products. It is, however, the best tool available to identify environmental trade-offs, and to show which are the relevant issues and environmental concerns for certain applications. LCAs thereby provide additional information to support decision making, either on a commercial level or on a political or policy level. LCAs can in this respect also be very useful to identify the preferred direction of innovation, technological progress might change the environmental impact of a product or process and this can be made explicit by LCA comparison of the existing and the provisioned process.

Looking at the available literature, a number of issues stand out:

Functionality of the biobased application is an important issue: there are a number of examples where the functionality of the biobased product is inferior compared to the alternative. Due to the inferior functionality in such cases usually more material is needed from the biobased alternative, which negatively influences the sustainability in the application under study. This influence can be unexpectedly large.

A matter of dispute lies in the question whether or not it is acceptable to assign the use of green energy to the sustainability of the production process. When wind power is used the production process seems to become more environmentally benign, while it still uses the same amount of energy. On the other hand, if the producer had not invested in using wind energy, the process would indeed use more non-renewable energy. Both views can thus be justified.

A number of papers present the use of biobased feedstock as a resource for the chemical industry. In this case the same material (and thus functionality) that is normally made from oil is now made from a biobased resource. A number of examples show that in this case it is definitely possible to gain on non-renewable energy use and greenhouse gas emissions, although eutrophication may come out more negative if biobased resources are used. For these kind of applications of biobased feedstock, a large gain in process sustainability by the use of industrial biotechnology is provisioned.

1 Introduction

Many methods have been developed for the evaluation of product sustainability. Generally, quantitative and qualitative methods can be distinguished.
Quantitative methods will enable very thorough comparison of products and will require large amounts of detailed information. Qualitative methods need far less information and can be used for scanning purposes. The Cramer criteria are a mix of quantitative and qualitative measures.

A scan of the available literature shows that up till now (summer 2008) very little work has been done and/or published on the sustainability of biobased high added-value products, whereas much more papers are available discussing the sustainability of biofuels.

In this report we present in chapter 2 a brief overview of the methods that are presently in use for evaluating sustainability. In chapter 3 we discuss more deeply the pros and cons of the various methods, with a strong focus on the LCA method. In chapter 4 we give an overview of the available literature on sustainability of high added-value products and present the main conclusions from this literature.

2 A short overview of methods used to determine sustainability

2.1 Introduction

Life Cycle Analysis is the most widely used quantitative evaluation method. Some methods show similarity to the Life Cycle Analysis methodology: emergy analysis and exergy analysis. Other methods also include financial parameters (eco-efficiency analysis) or risk inventory (eco-efficiency analysis, ecological fingerprint).
Next to the quantitative methods also qualitative methods are used to investigate and improve sustainability of products and processes. Qualitative methods usually have check lists that can help to detect unsustainable aspects of a process or product.
In paragraph 2.2 the various methods that are based on life cycle analysis are presented, paragraph 2.3 focuses on qualitative methods, whereas in paragraph 2.4 some methods that are presumably not fit for product evaluation are listed.

2.2 Life Cycle Analysis (LCA)

In general, Life Cycle Analysis produces an inventory (LCI) of all environmental loads of the product's life cycle (production, use and waste processing). The loads are then grouped together via weighing factors to yield impact equivalents (pollutants that are known to cause acid rain are expressed as SO_2 equivalents, pollutants that are known to contribute to the green house gas are expressed as CO_2 equivalents etc.). Subsequently, the environmental impact of the product of interest is compared to a product with the same functionality (Corbière-Nicollier *et al.* 2001, Curran 2003, Gustafsson and Borjesson 2007, Kim and Dale 2005, Petrini *et al.* 2007). Usually (a selection of) the following impacts are taken into account:

- Green house gas
- Stratospheric ozone depletion
- Acidification
- Photochemical smog
- Eutrophication
- Energy consumption (renewable and non-renewable)
- Human health
- Ecological health
- Resource depletion
- Degeneration
- Land use
- Water use
- Solid waste

Chapter 3.2 gives a more elaborated explanation including some ins and outs on Life Cycle Analysis.
The costs of a full life cycle analysis are very high. At the same time, different products might have very different scores on different impacts. Often the trade off of these different impacts is

disputable. Therefore, there is a considerable risk that even a full life cycle analysis will not provide definite answers.
In order to cut costs, several short cut methods can be used. In view of the present environmental issues, for a product to be sustainable it is essential that the GHG (green house gas) balance is better than the fossil alternative. Also the resource depletion should be lower. If these terms are not met, the product is unsustainable and evaluation of the other bullets is not needed.

Many methods show similarity to the LCA methodology. Some are part of LCA (LCI), others have a similar systematic approach but different system boundaries (Eco profiles).
Several methods were presented to weigh different impact categories into one single number: distance to target weighing, Eco-indicator, emergy analysis, ecological footprint analysis and ecosystem damage potential. Others provide tools to account for spatial impact differences: meso scale life cycle impact analysis.

2.2.1 Life cycle inventory (LCI)
The method of Life Cycle Inventory maps all environmental loads of a product (Landis *et al.* 2007). This method is especially suitable when comparing two processes that are more or less alike (ethanol from wheat vs. ethanol from maize, not fibre board with glass fibres vs. fibre board with natural fibres).

2.2.2 Eco profiles
The assessment of eco profiles is based on an LCA type method with different system boundaries. Only the production phase is evaluated (cradle to gate instead of cradle to grave). If products are very much alike (i.e. plastics with similar characteristics) the pollution during usage and in the waste stadium will be very comparable. Omitting the analysis of these phases can considerably reduce the amount of work in the LCA analysis (Vink *et al.* 2007).

2.2.3 Distance to target weighing methodology
The distance to target weighing methodology is a tool in LCA analysis that is meant to overcome the problem that occurs when two products have high scores on different impact indicators. It provides a method to weigh each impact by the apparent importance of the impact factor. Each impact factor is weighed by the distance to target: a high weight factor is given if the current impact is high compared to the desirable impact limit (Weiss *et al.* 2007). Usually the weighing of the impact factors is a political affair. With this method, the political struggle seems to be circumvented, but now the setting of the targets will shift into the political arena.

2.2.4 Eco-indicator
The Eco-indicator method is based on the LCA methodology. The method expresses environmental impact as mPt Eco-indicator score. There is a large database containing the impact in mPt of often used materials and processes. To obtain the impact of a product one can

simply add the impact of materials and processes used. This method is used a lot in industry due to its simplicity (www.pre.nl). Weighing of the various impact categories is done through the distance to target method (paragraph 2.2.3)

2.2.5 Emergy evaluations

Emergy is the amount of solar energy needed to obtain a product or support a regional system (Marchettini *et al.* 2007). It enables to account for economically free energy flows that usually are ignored by other methods.

2.2.6 Ecological Foot Print Analysis (EFA)

This method starts from LCA analysis. All impacts are translated to an area that would be needed to supply resources and assimilate wastes without impairing the ability of a region to continue to provide services (Huijbregts *et al.* 2007, Marchettini *et al.* 2007, Venetoulis and Talberth 2006). It enables the trade off of different types of impacts. However, it cannot handle mining and recalcitrant pollutions.

2.2.7 Ecosystem Damage potential

Land use change is considered one of the impact factors as summed in paragraph 2.2. The Ecosystem damage potential is a method to indicate the damage caused by land use change (Koellner and Scholz, 2007).

2.2.8 Meso scale life cycle impact assessment

Meso scale life cycle impact assessment adds a space differentiation to LCA analysis. The spread impact of eutrophication on a sea might not be as much of a problem as the local impact of eutrophication on a vulnerable wilderness area. High local impacts might be a reason to abandon some process in favour of another (Sarigiannis and Triacchini 2000).

2.2.9 Eco efficiency analysis

Eco efficiency analysis compares the economical costs and environmental benefits of process alternatives. Processes are depicted as dots in a graph with normalized costs on the X-axis and normalized environmental impacts on the Y-axis. Processes with low environmental impact at low costs will appear in the lower left corner of the plot. Thus the process that reduces the environmental impact most efficiently, is easily selected (Wall-Markowski *et al.* 2004). The following issues are regarded:

- Resource composition
- Energy consumption
- Emissions
- Risk potential
- Health effect potential
- Land use

2.2.10 *Ecological fingerprint*

A spider plot is made, with a normalized representation of environmental impacts of different process alternatives (Wall-Markowski *et al.* 2004). On the axes are:

- Resource composition
- Energy consumption
- Emissions
- Risk potential
- Health effect potential
- Land use

It is immediately clear where the impacts of processes are more or less equal and where one process performs far better or worse. The method (just like LCA analysis) is not very helpful if one process has a very high impact on one item and another process has a very high impact on another item.

2.3 Qualitative methods

Next to the quantitative methods presented in paragraph 2.2 also qualitative methods are used to investigate and improve sustainability of products and processes. Qualitative methods usually have check lists that can help to detect unsustainable aspects of a process or product.

2.3.1 *Principles of green chemistry*

A sustainable process should comply with the principles of green chemistry. The intended process is scanned for unfavourable characteristics that will have a large impact on LCA performance (Anastas and Kirchhoff 2002, Warner *et al.* 2004). For example: if the atom economy is high, the LCA analysis will usually turn out better for less resources will be needed to produce the product and less wastes will be produced. Issues that are taken into account in the principles of green chemistry are:

- Prevent waste
- Atom economy
- Less hazardous synthesis
- Safer chemicals
- Safer solvents and auxiliaries
- Energy efficiency
- Renewable feedstocks
- Reduce derivatives
- Catalysis
- Design for degradation
- Real-time analysis for pollution prevention
- Inherently safer chemistry for accident prevention

2.3.2 *Critical components*

For the production of sustainable biobased products from forests a list of issues that should be taken into account was made by Mayfield *et al.* (Mayfield *et al.* 2007):

- Sustainable biomass production
- Sustainable forest operation
- Product delivery logistics
- Manufacturing and energy production
- Environmental sustainability
- Consumer demand
- Rural economic development
- Marketing
- Infrastructure
- Community engagement
- Incentive support
- Collaboration
- Education

2.3.3 *Conditions for the sustainability of biomass based fuel use*

Biomass production can only be sustainable if the following essentials are satisfied (Reijnders 2006):

- Soil is preserved
- Soil organic matter content is kept constant
- Nutrient levels are preserved
- Little fossil fuels are used during harvest and processing
- Water reserves are preserved

2.4 Presumably unfit methods

Some methods are reported to be unfit for product evaluation. They are named here, for the sake of completeness.

Only helpful if the product is heat or electricity:

- Ecological Cumulative Exergy Consumption (ECEC) (Ukidwe and Bakshi 2008)
- Industrial Cumulative Exergy Consumption (ICEC), (Ukidwe and Bakshi 2008)

Only helpful if the product is heat, electricity of fuel:

- Exergetic analysis, (Hepbasli 2006), Strong focus on energy, electricity and fuel products.
- Life cycle energy efficiency, this method is only suitable for evaluation of fuels (Malca and Freire 2006).

Partial solutions:

- HHS (Health Hazard Scoring), MIPS (Material Input Per Service-unit), SEP (Swiss Eco-Points), SPI (Sustainable Process Index), SETAC (Society of Environmental Toxicology and Chemistry's Life Cycle), EPS (Environmental priority system), (Hertwich *et al.* 1996)

Describes the similarity/congruence of environmental indicators:

- Principle Component Analysis (PCA) This method seems to be unfit for product evaluation (Bastianoni *et al.* 2008)

3 Measuring sustainability of products

3.1 Introduction

In this chapter a further introduction into the LCA analysis is given in paragraph 3.2. Paragraph 3.3 discusses some pros and cons of the LCA method.

3.2 The LCA analysis

3.2.1 How to perform an LCA.

An LCA analyses the environmental impact of the total life cycle of a product from "cradle-to-grave". For the analysis two ISO standards are available:

- ISO 14040, Principle and frameworks
- ISO 14044, Requirements and guidelines.

An LCA is performed in 5 stages (see figure 3.1):

- Goal definition
- Inventory
- Classification
- Evaluation
- Analysis.

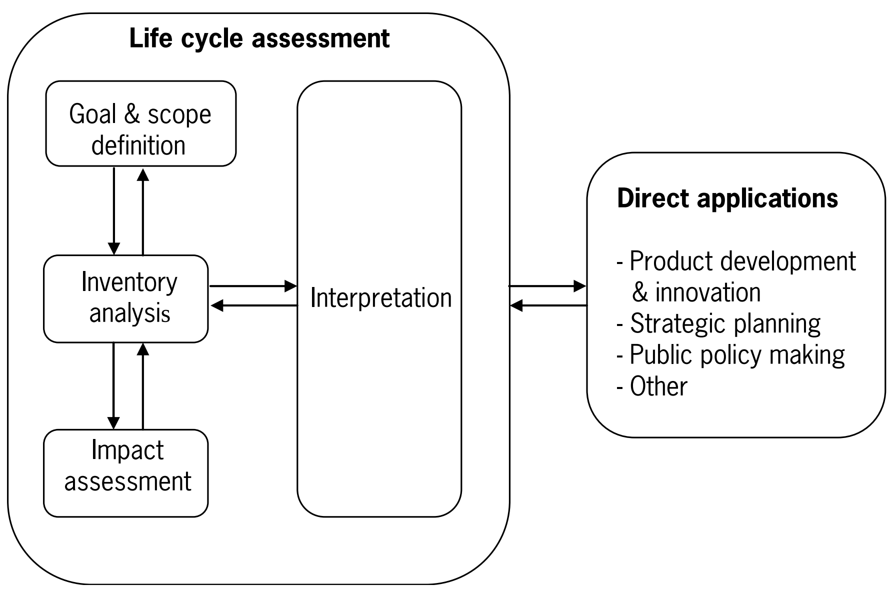

Figure 3.1. Overview of the life cycle assessment. The impact assessment phase contains both the classification and (if performed) the analysis stage.

3.2.2 The goal definition stage

In the goal definition stage the aim and scope of the study are determined. This requires the definition of the function and the functional unit of the studied product. For instance if we want to compare plastic cups with earthenware cups, we could determine the impact of production of a plastic cup versus an earthenware cup, but we could also determine the impact of serving 1000 cups of coffee from a vending machine using single use plastic cups versus multi use earthenware cups. These two studies will give very different outcomes.

This immediately brings up the issue of the system boundary. In the first example the system only involves the production of the cups, assuming the cups will both be used in the same way, in the second example the system also involves a specific use of the cups. The way the system boundary is defined can have an enormous impact of the final outcome of the study. Figure 3.2 shows an example from a study performed by IFEU in Heidelberg for Natureworks LLC (IFEUNatureworks 2008). In this study food containers produced from different plastics were

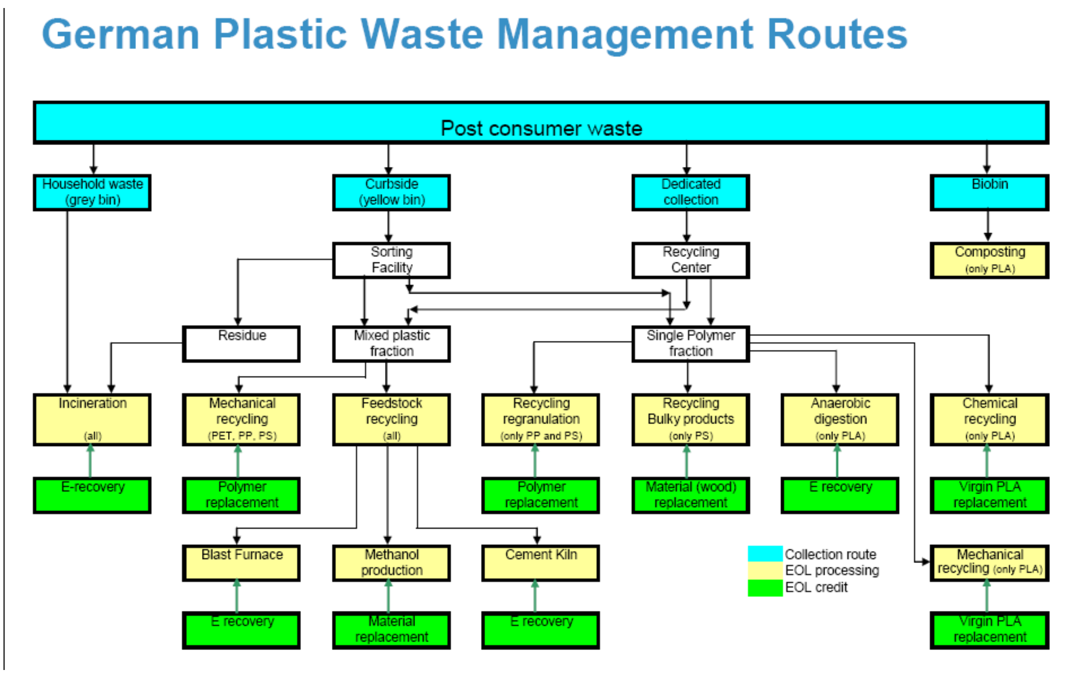

Fig. 3.2. The German consumer waste management system differs significantly from the Dutch situation. This influences the outcome of an LCA study (Source IFEU/Natureworks, www.natureworksllc.com).

compared. The comparison was made for Germany. As figure 3.2 shows, the waste management routes in Germany are very different from the Netherlands. Therefore the outcome of such a study might differ significantly between Germany and the Netherlands. *This implies that it is often impossible to generalise the outcome of an LCA study.*

3.2.3 *The inventory stage*

In the next stage, the inventory stage, a model of the product life cycle is made, including production, transport, use and disposal. From this model a list of all polluting emissions and consumption of resources and energy per functional unit (and within the system boundary) is made. This stage is also called the Life Cycle Inventory (LCI) stage. Sometimes the LCI is the end of the analysis. This can be done when comparing two very similar processes to produce the same product (ethanol from wheat vs ethanol from maize, for instance).

3.2.4 *The classification stage*

In the classification stage first the relevant impact categories are selected. In different studies often different impact categories are used. Common categories of assessed damage are: global warming (greenhouse gases), acidification, smog, ozone layer depletion, eutrophication, ecotoxic and anthropotoxic pollutants, desertification, land use as well as depletion of minerals and fossil fuels. However, one is free to make a selection of impact categories most relevant for the product under study. In the next step the environmental impacts that were determined in the inventory stage are grouped under the relevant impact categories. An example is shown in figure 3.3, where various inputs and outputs of a product life cycle are grouped under the corresponding impact categories. The in- and outputs are then aggregated within the impact categories using a classification factor, which reflects the degree to which they contribute to the category (for instance methane, CH_4, is about twenty five times more effective as a greenhouse gas than CO_2, methane output is therefore multiplied by a factor before aggregation (figure 3.4). The result of this phase is an environmental profile, listing for each environmental effect one numerical value.

	Cumulative Energy Demand	Ressource consumption	Climate Change	Summer smog	Eutrophication 1)	Acidification	Human Toxicity	Human Toxicity	Use of Nature
	CED fossil	Crude oil	CO_2 fossil	CH_4	NO_x	NO_x	As	PM_{10}	Area
	CED nuclear	Natural gas	CH_4	NMVOC	NH_3	NH_3	B(a)P	SO_2	Farm Land
	CED renewable	Brown coal	N_2O	Benzene	COD	SO_2	Cd	NO_x	
		Hard coal	C_2F_2	Formaldehyde	N-Comp.	TRS	Cr 2)	NH_3	
			CF_4	Ethyl acetate	P-Comp.	HCl	Ni	NMVOC	
			C_2F_6	VOC		HF	Dioxin		
			CCl_4	C-total		H_2S	Benzene		
			R22	Ethanol			PCB		
				NOx					
Units	MJ	kg crude oil eq.	kg CO_2 eq.	kg ethene eq.	kg PO_4 eq.	kg SO_2 eq.	kg As eq.	kg PM10 eq.	m^2 /year

1) NO_x (calculated as NO_2) and NH_3 => terrestrial eutrophication; COD, N, P => aquatic eutrophication
2) as Chromium VI

Figure 3.3. Grouping of in- and outputs of a product life cycle under the corresponding impact categories. The red units are the units into which the results are aggregated (source IFEU, Heidelberg, Guido Reinhardt)

	GWP$_{100\ years}$ g CO_2-eq/g	AP g SO_2-eq/g	EP g PO_4^{3-}-eq/g	POCP g C_2H_2-eq/g
Emissions to air				
CO_2	1	–	–	–
SO_X	–	1	–	–
NO_X	–	0.7	0.13	–
NH_3	–	1.88	0.35	–
CO	2	–	–	0.04
CH_4	23	–	–	0.007
HC		–	–	0.4
N_2O	296	–	–	–
HCl	–	0.88	–	–
Emissions to water				
NO_3^-	–	–	0.10	–

Figure 3.4. Example of multiplication factors used in a study on wood coatings. GWP is global warmin potential, AP is acidification potential, EP is eutrophication potential, POCP is Photochemical oxidant creation potential. (After Gustafsson and Börjesson 2007).
Note that an emission can contribute to more than one impact category.

3.2.5 The evaluation stage

The next stage, the evaluation stage is voluntary according the ISO standard. In this stage the various effects are normalized to provide a basis for comparing different types of environmental impact categories (all impacts get the same unit). The various effects can then be weighed among each other, which implies assigning a weighing factor to each impact category depending on the relative importance. *This last step is no science but politics: who decides which is worse, how do you weigh human toxicity versus climate change?*
However, trying to aggregate the environmental profile into one value of environmental impact can be tempting, since it is difficult to compare two products with the same functionality, that contribute to very different impact categories. This is often the case when comparing biobased products to fossil based products, where biobased products tend to contribute relatively strongly to eutrophication and acidification whereas mineral based products usually contribute more strongly to resource consumption and climate change.
Five of the methods presented in chapter 2: The Distance to target weighing methodology, the Ecoindicator methodology, the Emergy analysis, the Ecological Foot Print Analysis (EFA) and the Ecosystem Damage Potential are all methods that try to rework the data from the LCA analysis into one impact category or one impact factor.

3.2.6 The analysis stage

In the analysis stage the results are interpreted and the uncertainties in the results are estimated. A sensitivity analysis needs to be done with variations on the base scenario in order to show the parameters that are the most important contributors to the environmental impact.

3.3 Issues surrounding the LCA analyses

There are a number of issues one might bump into when performing an LCA analysis, some of which were already mentioned in the previous paragraph:

- system boundaries,
- data variability and uncertainty
- functionality of a product and its alternatives,
- assignment of environmental impact in case of multiple products,
- weighing of various very different impact categories against each other and
- "who paid for the study".

Each of the issues will be discussed in the following paragraphs.

3.3.1 System boundaries

As discussed in the previous paragraph, the outcome of an LCA analysis can depend very strongly on the definition of the system boundaries. This has a number of implications.
In the first place it implies that it is often not possible to generalise the results of a study of a certain product in a certain application. Using the same product for a different application, even if it is a very similar application, or in a different country may render different results.
Furthermore, it is not always straightforward where the system boundaries need to be drawn. For instance in the application of agrofibre reinforced composites in automotive applications the largest contribution to sustainability is a secondary effect: namely the fact that it is possible to design lighter parts from these materials than from their alternatives. In this way, during the lifetime of a car, a significant amount of petrol can be saved. But to find this effect, the system boundary needs to be stretched beyond just the function of the product in the car. As we will see below the problem of defining the proper system boundaries becomes even larger when multiple products are made from the same resource.

3.3.2 Data variability and uncertainty

Variability in the actual inventory data may be related to different production methods available to produce the same components. It may also arise from other variables that may affect process efficiency and effectiveness, like quality of resources, ambient temperatures, humidity etc.
Furthermore different data types used in LCA have different validity. One could use site-specific (primary) data, collected by a practitioner on site, but it can be very difficult to get people to share their information on a specific process, for instance for reasons of business competition. Data may also be collected from different, but reasonably similar processes in case of the absence of primary data. Also estimated data, based on an experts best judgement may be used. The different levels of uncertainty in the data used, will affect the assurance one has in the conclusions that can be derived from the data set. The consequences of this can be difficult to judge. Curran (2003) states that due to this, comparison between systems should not distinguish between systems that are different by less than an order of magnitude.

3.3.3 *Functionality of the product and its alternatives*

When comparing two different materials for the same application, one has to take into account the difference in properties, which may influence the design of the product. An example is the use of agrofibres for wind turbine blades. The agrofibres need to replace the glass fibres that are presently used. But since the agrofibres have much lower strength than the glass fibres, the whole blade needs to be designed twice as thick, doubling its environmental impact by almost a factor of two. On the other hand, when agrofibre reinforced composites are used in an application where stiffness is important, for instance in interior panels for cars, the panels can be designed thinner than the corresponding glass composites, since the stiffness of agrofibres is relatively high. In this case also petrol can be saved during the service life of the car, because the car can be designed lighter.

Especially in studies that compare an existing material with a material that is still in development, and is not really used in a product at present, this fact is easily overlooked. This problem can be more or less avoided when comparing the materials on the basis of equal functionality (for instance equal strength of the produced part), taking the most limiting functionality-difference as basis (Ashby, 1999).

Although this all might seem obvious, there are a number of examples of publications that overlook this fact. The conclusions of these studies are thus not valid.

3.3.4 *Assignment of impact in the case of multiple products.*

There are many examples, especially in the use of biomass, where from one feedstock multiple products are made. Usually a side stream of one production step is the input for another production step. (see figure 3.5). One kilo of crop thus provides resources for a number of

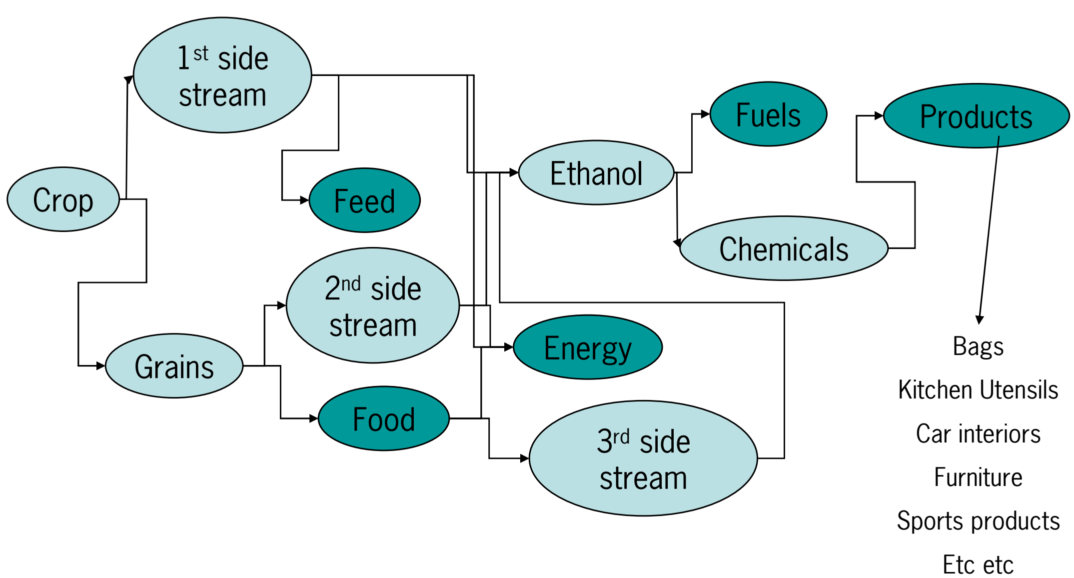

Fig. 3.5. Multiple products produced from one crop.

products at the same time. In this case it can be very difficult to decide how to assign the environmental impact to the various products, how do you distribute the emissions over the different products? How this allocation is done can significantly influence the environmental impact of a product.

Various approaches can be taken:

- on basis of weight
- on basis of volume
- on basis of energy content
- on basis of economical value
- on basis of demand

Each of these approaches yields different answers for the various products in the portfolio. There is not one method which is "best", it depends on the situation. This is understandably a source of existing very large differences in literature values of the sustanability of various products.

Also in some cases the question "what does it substitute" can be relevant, a product might get credits if it substitutes something which has a high environmentel impact. However, to answer this question the system boundary needs to be expanded and this can make the study very complicated, time consuming and expensive.

An interesting example is the production of algae in a bioreactor. The production costs with present technology more energy than the energycontent of the algae, even for a high production rate, 1 kilogram dry-weight of algae costs 1 liter of fuel oil, so the use of these algae for biofuels is presently not a sustainable option. However, algae contain omega-3 fatty acids, which is usually won from fish. The energy input to catch a kilo of fish (dry weight) with a fish borer is roughly 10 liter of fuel oil. With algae as a source of omega-3 fatty acids, thus 90% of energy reduction can be reached.

Yet another issue here is how to judge the carbon in a biobased product. One might consider this as sequestration of green house gas, but one might also consider this as a neutral effect, and not take it into account in the study. Both approaches are taken in literaure.

3.3.5 Who decides which is worse: comparing apples and pears

The classification phase of an LCA study leads to an environmental profile of the product under study, listing for each environmental effect one numerical value. The step to aggregate these impacts withín the impact categories can already lead to scientific debate on how much the different outputs (substances) contribute to certain effects. However, this is still relatively straightforward. It gets really complicated when one tries to compare one impact category with another, which are not at all comparable, for instance eutrophication with depletion of fossil resources. Many studies choose to present the data as the environmental profile, showing for each impact category the impact of the system under study. Figure 3.6 shows the profiles of different cups, one way or recyclable and different materials, to be used on an event. It is impossible to make an unambiguous statement about the preferred cup system, since no cup scores best in all categories. This is difficult when the study is used to support selection between

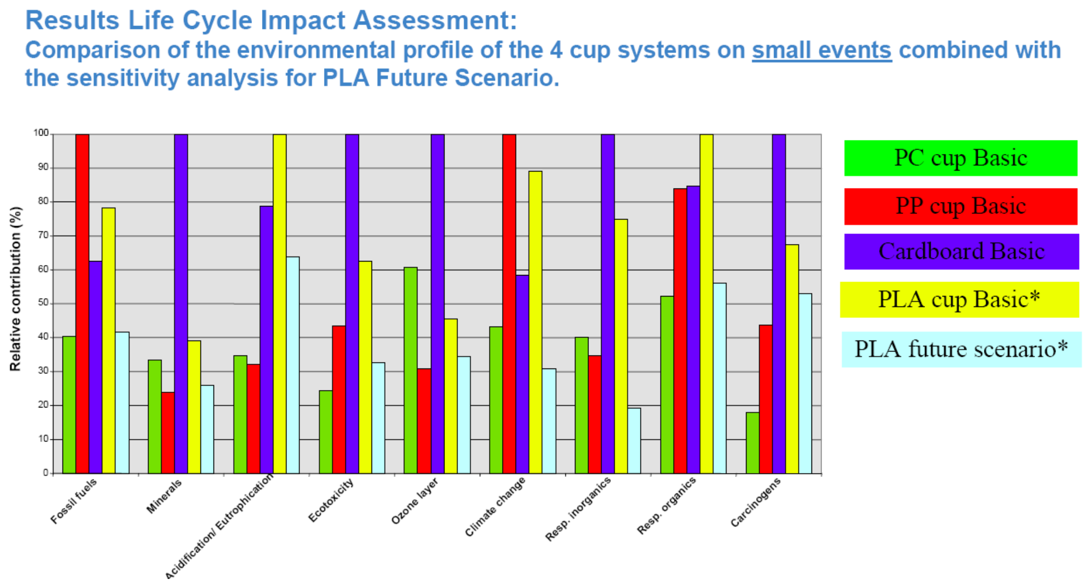

Figure 3.6. Comparison of 4 different cups, used on a small event(f.i. a concert). It is impossible to make the perfect choice, since no cup scores best on all categories (Source OVAM/NatureworksPLA, available at www.natureworksllc.com)

a variety of options. Therefore a number of methods were developed to integrate the environmental profile into one number.

One of the methods is the distance-to-target method. In this approach a desired level of maximum polluting emissions per category is determined, the target. This can be determined for instance on European level. Next the distance of the present level of polluting emissions to the target is determined per environmental impact category. Then a weighing factor is assigned to each impact category which is higher when the present distance to the desired target is larger. The different categories can then be combined into one number. This approach is also used in the subsequent Ecoindicator methods (Ecoindicator 95, Ecoindicator 99).

It is tempting to use these methods and draw your conclusions on basis of the numbers provided, however you should be aware that someone else now has decided for you which impact category is worse.

A rough rule of thumb can be assigned to the product price; the more expensive the product, the more energy and resources presumably were needed to produce it, and thus the higher its environmental impact will be. This can give a useful first impression especially when comparing different materials.

3.3.6 Who paid for the study?

A final issue to be raised is the question of the independency of the study. Since many choices need to be made during the study concerning system boundaries, allocation of impacts, etcetera, the outcome of a study can always be a matter for dispute.

The performer of the study can take measures to diminish the chance on discussions. It is important to carefully define the functional unit, write a transparent report, phrase the conclusions carefully, cooperate with experts and stakeholders and arrange a peer review of the study and include it in the report.

Nevertheless, in issues where the stakes are high, the outcome of an LCA will always be a source for dispute.

4 Product specific evaluations

4.1 Introduction

A rather extensive literature search was done in august 2008. It turned out that only a few sustainability analyses on high added-value products from biomass have been published up till now. The main conclusions of these studies will be presented in this chapter. In some cases also some comments on the paper, the method or the conclusions are given.
Some studies were only presented on conferences and are not published yet. These are not included here, because they are not readily accessible. Furthermore the more extensive literature on the sustainability of biofuels is not covered here, as it is outside the scope of this report.

4.2 Hemp fibre reinforcement, LCA (Wötzel *et al.* 1999)

This scientific paper compares a side panel (door) for the Audi A3 made from injection moulded ABS versus a hemp epoxy composite part containing 66 wt% of hemp fibre, with the eco-indicator 95 method. The authors conclude that emissions for both materials weigh similar, but that the hemp part performs better on energy and material input. The environmental impact of the production of the fibres is insignificant relative to the complete ecobalance. The hemp part can be improved by replacing the epoxy with a more environmentally friendly resin. Further ecological advantage results from the weight difference of the parts, the hemp part is lighter and thus leads to reduction in fuel consumption during use.
Despite having presumably the same end-product functionality, the production routes of the two products that are compared are very different. The choice for these two materials systems seems quite arbitrary, other commercial systems are also available.

4.3 Biofibres (China reed) vs. glass fibres, LCA (Corbière *et al.* 2001)

In this study two hypothetical transport pallets from fibre reinforced PP (polypropylene), one containing glass fibres the other china reed fibres are compared, using a variety of LCA related methods. Also, attention is paid to the influence of end-of-life scenario. The natural fibre composite is found to have a better environmental profile (as long as the life time is longer than 3 years) except for land use. The influence of the matrix material PP on the environmental profile of the pallets is substantial, both for the glass as well as for the natural fibre pallet.
The authors admit that the natural fibre pallet does not exist as yet and that, with present technologies the part will need to be designed thicker to reach enough stiffness, thus increasing its environmental impact.

4.4 Natural fibres and PTP, LCA, (Mussig *et al.* 2006)

This paper describes an experimental body panel for a bus. A composite made from hemp with a commercial epoxy resin made from renewable resources (PTP) is compared to a standard glass fibre polyester (UP) SMC (SMC is a widely used production technique for larger composite panels like body parts for automotive, baths and showers etc.). The authors conclude that for the impact categories non-renewable resources, cumulative energy demand, greenhouse gas, summer smog, acidification and human toxicity, the PTP panel scores significantly better that the UP panel. Only for the category Eutrophication the UP panel is slightly better. The authors conclude that indeed it is possible to make a large body part with the natural system based on SMC technology. However, the strength and impact resistance of the experimental body part are below standard. The stiffness is within range of the standard, and the weight of the part is significantly lower. The authors thus show that it is technically feasible to produce a large part from renewable resources, which has a better environmental profile than the fossil alternative, but more development still needs to be done, the present panel is not good enough to be applied.

4.5 Flax fibre composites versus glass fibre composites (Bos 2004)

In the PhD thesis of Bos a chapter is devoted to the environmental performance of flax fibre composites as compared to glass fibre composites. The analysis is based on the Eco-indicator 95 method, which expresses the environmental impact in one number. Bos defines a performance specific impact indicator, which expresses the amount of environmental impact for a certain level of strength or stiffness. Since flax fibres are relatively stiff and lightweight, but much less strong than glass fibres, the conclusion follows that for application where stiffness is needed, flax fibre composites are environmentally preferable, whereas when strength is needed, glass fibre composites are the more sustainable choice. This is due to the fact that to produce an equally strong product from flax fibre composite, much more material would be needed, strongly increasing the environmental impact. Also here, as in other studies, the conclusion is that the resin, which acts as the binder in the composite, has a much higher environmental impact than the fibres.

4.6 Sorona Polymer sustainability story, Energy and GHG savings (Dupont)

In contrast to the other evaluations presented here, this is an information sheet from Dupont on one of their products Sorona. Sorona is presently for approximately 40% biobased. Dupont concludes that the production (cradle-to-gate) of the biobased component (PDO) from biomass instead of from fossil feedstock saves 40% energy and 20% greenhouse gas. Furthermore, the outcome of a (peer reviewed) cradle-to-gate study of Sorona vs nylon 6, is presented. Sorona saves 30% non-renewable energy consumption and 55% greenhouse gas emission.
The comparison of Sorona with nylon-6 seems quite arbitrary, they are not the same type of polymers (polyester vs. nylon) and also the application area of these two materials is not necessarily the same. Furthermore, nylon-6 has compared to other polymers a relatively high environmental impact. Comparison versus another polyester might be more logical. Environmental advantages in the use phase (man-made fibres take considerably less energy for washing and drying), are not presented.

4.7 Polyhydroxyalkanoates (PHA), LCA (Kim and Dale 2005)

In this study, first a critical review is presented of other LCA studies on PHA, and then the authors try to do a better job. They compare PHA to a conventional plastic, polystyrene, and

they also compare present day resources (corn grain) to future resources (corn grain + stover) and future fermentation technology. They conclude that with present day technology, the environmental impact of PHA is similar to that of polystyrene, but that improved fermentation technology and other feedstock will significantly improve the environmental performance of PHAs. The environmental impacts taken into account are non-renewable energy, global warming, photochemical smog, acidification and eutrofication.
The authors include in their analysis also the avoided environmental burden of alternative products for the co-products of the wet milling process. This process produces dextrose as feedstock for PHAs but also a number of other products.

4.8 Poly(3-hydroxybutyrate)-based (PHB) composites, LCA (Petrini *et al.* 2007)

In this study an LCA is done for PHB based composites, with either sugarcane bagasse or nano-clays as filler. The materials are compared to high-impact polystyrene (HIPS) in a cathode ray tube and to glass-fibre filled PP in an interior car panel. Non-renewable energy use and global warming are considered. The relatively poor properties of the PHB composites, negatively influence the environmental performance but due to savings in the production process for PHB environmental benefits can still be gained. Due to the low stiffness and high density (and thus weight) of PHB, the PHB composite does not give an environmental benefit over the glass fibre PP panel in transport application.

4.9 PLA, Eco profiles, GHG, primary energy, LCI, Ecoprofiles (Vink *et al.* 2007 and Vink *et al.* 2003)

Vink has published two papers on the environmental impact of the production of polylactic acid (NatureWorksPLA) from renewable resources. Focus lies on non-renewable energy consumption, greenhouse gas emission and water use. The results are compared to a range of fossil based polymers. PLA performs rather well on these indicators. In the non-renewable energy consumption, both the oil needed for fuel to produce the polymers as well as the oil needed as feedstock is taken into account. PLA produced with present technology has a lower fossil renewable energy requirement than the other 11 (petrochemical) polymers to which it is compared. Greenhouse gas emissions are in the same range as the lowest petrochemical polymers (PE and PP). Water use is comparable to bottle grade PET, PP ad PE. Only fibre grade PET is lower. The papers also estimates the improvements in environmental impact that can be gained by applying newer technology and renewable energy (wind power), and which are significant. The allocation of the use of wind power to the PLA is disputed by some people, since the energy requirement of the process itself does not decrease by simply using another (greener) source.

4.10 Motor oil, wall insulation, asphalt coating, transformer oil, general purpose cleaners, fuel additives, LCA, (Curran 2003)

This paper, from the US environmental Protection Agency, gives an overview of recent American studies into the sustainability of a number of alternatives for various applications, including in most cases a biobased alternative. The examples chosen show that a biobased

alternative is not necessarily the most sustainable option. For instance in comparing motor oil, to recycled motor oil to biobased motor oil, the recycled motor oil performs best in most categories. In the case of transformer oils, all three products investigated (mineral oil, soybean oil an silicone fluid) have different impacts in different categories. Whereas it is clear that the silicone fluid is the most unsustainable option, the best choice between the other two oils is not easily made.
Next to the more or less standard LCA methods also a coarser approach is presented: a screening level approach. In this case a mixture of quantitative and qualitative generic data is used. The intent of the screening is to provide "directional" information regarding the environmental trade-offs between alternatives and highlight where the most significant impact areas occur.
The author concludes that LCA is a good tool to support decision making between a variety of alternatives for a preferential buying policy, but that the decision is not made by the LCA itself. Other factors need to be included as well, such as competing claims.

4.11 Wood surface coatings, LCA, (Gustafsson and Borjesson 2007)

This paper presents a study on wood coatings, based on the production conditions of AKZO Nobel in Copenhagen, and application of the coatings in Goleniow in Poland at an IKEA factory. The authors warn not to use the results for any far reaching conclusions of the systems under study in general. Two wax-based coatings -one of which a not commercially available biobased wax, produced from rape-seed oil- and two UV-hardening lacquers (one 100% and one waterbased) are compared. The 100% UV coating is in a dry form and very little is needed to coat a surface, from the wax 9 times more is needed, from the waterbased UV 15 times as much is needed. Also the wax coating is estimated to last five years, and thus is estimated to be applied four times over twenty years, whereas the lacquers are applied only once. The authors have done a very thorough investigation of all aspects of production and application of the coatings. The impact categories studies are global warming, acidification, eutrophication, photochemical oxidants and energy consumption. The 100% UV coating comes out as the most sustainable option in all impact categories. The authors also show in a sensitivity analysis the effect of assuming that the life time of the lacquers and the coating would be the same and the effect of moving the application of the coating from Poland to Sweden, where the energy mix is much greener. Both changes have a drastic effect on the calculated environmental impact of the various coatings, but do not change the conclusion that the 100% UV lacquers performs best in all categories. The authors furthermore state that if the 100% UV lacquer would be produced from renewable building blocks, an even lower environmental impact might be reached.

4.12 Vitamin B2, polyester, Eco efficiency analysis, (Wall-Markowski 2004)

This is a typical paper from a company. It presents the eco-efficiency analysis as it is used by BASF for the evaluation of possible new production routes and new products. Not only the environmental performance, but also the costs are taken into account, to support business decisions. Quantitative information of the presented examples is not given, so it is not possible to judge the outcomes of the study. However, a warning is given that biobased products are not always the most sustainable choice.

4.13 Biobased bulk products, NREU, REU, LU and GHG (Hermann *et al.* 2007)

This very interesting paper presents the environmental impact of current and future technology routes leading to 15 bulk chemicals (including ethanol, butanol, ethylene, etc) , using industrial (white) biotechnology. The paper focuses on non renewable energy use and greenhouse gas emissions. Already with current technology green house gas emissions are reduced when using fermentable sugars as resource for a number of chemicals with future technology these savings obviously increase. The authors further stress the fact that when judging renewable resources also land use must be taken into account. If for instance land use becomes limited, land use should be minimized for a certain amount of greenhouse gas to be saved. The authors conclude that putting greenhouse gas and land use first, succinic acid, caprolactam, PLA and butanol are the most attractive chemicals.

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