5

Introduction to Life Cycle Assessment

5.1 Principles of LCA

5.1.1 How to Assess Environmental Impact

Environmental awareness of our industrialised societies has been developing rapidly for the last several decades. A shift in attitude towards the environment has brought a new term – *environmentally friendly*. Although a commonly-used description, it is not easy in fact to determine which products or, in broader context, which forms of human activity, are environmentally friendly. Another crucial issue is to find out what can be done to improve the environmental profile of a certain product or process. How can we assess possible benefits gained by changing the mode of production, usage or disposal of a product. In other words: how do we determine which one of several alternatives is more, or the most, environmentally friendly. Answers to such questions are important for a sustainable development.

It has been proved that when evaluating the environmental friendliness of a product, intuition is not enough. In a survey on green milk packaging a majority would certainly find a returnable milk bottle much preferable to a disposable milk carton. The reason is that the bottle is recyclable and the cardboard cartons are not. The bottle is therefore expected to lead to significantly lesser amounts of waste in comparison to cardboard cartons. These two environmental problems – recycling and waste production – are broadly reported in the mass media. In reality the overall difference between the alternatives is insignificant. The two kinds of packaging contribute to completely different environmental impacts. Admittedly, glass can be reused and recycled, but it is connected with high costs of transportation and cleaning. This is not the case for disposable cartons. In conclusion, the most advisable solution would combine the environmental advantages of the two considered alternatives, namely being recyclable but at the same time light (for instance a square polycarbonate bottle) [Heijungs et al., 1996]. The environment is a complicated network of many unexpected and unexplained interrelationships. Sometimes a solution which appears to be excellent might only shift the problem to another life stage of the product, or to another sort of impact.

Life cycle assessment (LCA), is a rather new tool in environmental management, which has the capacity – at least in principle – to answer these seemingly easy questions: Is a product environmentally friendly? Which product is greener? What is then life cycle assessment and how can it be used. These are the questions we will address in this chapter.

In this Chapter

5.1.2 Definitions of LCA

According to the ISO DIS standards, LCA is defined as a method for analysing and determining the environmental impact along the product chain of (technical) systems. It includes the various types of technical conversions that occur in the manufacturing process. These consist of the *change of material chemistry* (chemical conversion), material formulation, or material structure; *the removal of material* resulting in an increase of (primary) outputs over the inputs; and the *joining and assembly of materials* resulting in a decrease of (primary) outputs over the inputs. This general description has been specified in two widely known definitions of LCA.

According to ISO 14040, the formal definition of LCA is as follows:

"LCA is a technique for assessing the environmental aspects and potential impacts associated with a product by:

- Compiling an inventory of relevant inputs and outputs of a product system.
- Evaluating the potential environmental impacts associated with those inputs and outputs.
- Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study."

The definition by SETAC (Society of Environmental Toxicology and Chemistry), which was a pioneer in publishing its "Code of Practice", states that:

"Life Cycle Assessment is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing, extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal."

Since the late sixties and early seventies much attention has been given to life cycle technology. Over the years life cycle assessment has developed (Box 5.1). It means that the analysis called LCA gathers a number of more or less different methods. What they have in common is the holistic viewpoint on the life cycle and dealing with environmental aspects of all emissions and material consumption resulting from the life cycle. Nevertheless, there is still no internationally accepted methodology of LCA. The international standard now developing is based on the ISO 14040 series.

With respect to the way of conducting an LCA we can separate qualitative and quantitative methods [Jensen et al., 1997]. *Qualitative methods* draw conclusions straight from the life cycle. The *quantitative methods* evaluate the environmental impacts by mathematical processing of the data describing the life cycle. They may even result in the calculation of a single score representing the environmental friendliness of a product.

LCA in Brief

LCA is a technique for evaluating the *environmental effects* of a product or a service over the entire period of its *life cycle* ("from cradle-to-grave").

5.1.3 The Goals and Applications of LCA

LCA assess the environmental effects of a product or service or, more commonly, the effects of a change in the production or design of a product or service.

The *goals and applications of LCA* range over a scale from short to long term. It includes:

- Short-term process engineering.
- Design and optimization in a life cycle (type 1).
- Product comparisons including product design and product improvement.
- Eco-labelling in the medium and long term (type 2).
- Long-term strategic planning (type 3).

Each goal requires its own type of analysis and modelling. Data requirements can then be specified more precisely, both for case applications and for generic databases.

Thus when performing an LCA, all the emissions and the resource consumption which enter or leave a life cycle are translated into the environmental problems that they potentially may contribute to. The two terms environmental effects and life cycle both need to be properly understood.

Environmental effects are the consequences of a physical interaction between a system studied and the environment. In practical use all environmental effects are represented by several categories of environmental problems. The most commonly used are:

- Resource depletion
- Global warming
- Ozone depletion
- Human toxicity
- Ecotoxicity
- Photochemical oxidation
- Acidification
- Eutrophication
- Land use
- Others (including solid waste, heavy metals, carcinogens, radiation, species extinction, noise).

The other term, crucial to understanding the holistic approach of the life cycle assessment, is the *life cycle* itself. It encompasses all the processes required to fulfil the function provided by a product or service (Figure 5.1), [Stachowicz, 2001; Walz, 2000].

At present LCA is used for the following fields of application:

- Infrastructure
- Process industry
- Energy production
- Transportation
- Heavy industry
- Consumer goods
- Livelihood

Box 5.1 The History of Life Cycle Assessment

Several tools for assessing environmental impacts

The roots of Life Cycle Assessment reach back to the 1970s. At the time methods such as integral environmental analysis, ecobalances, resource and environmental profile analysis etc were used. Over the years the experiences of working with these tools fed into the Life Cycle Assessment method around 1990. At a conference organised in 1991 by the Society of Environmental Toxicology and Chemistry (SETAC) it was agreed that the proper name for LCA should be Life Cycle Assessment (rather than Analysis). In 1997 the International Organisation for Standardization published its first standard for LCA , ISO 14040.

LCA is one of several tools for assessing the environmental impact of a product or service. Others include Environmental Impact Assessment (EIA), Ecological Risk Assessment (ERA), Material Flows Analysis (MFA) as well as several more economic tools such as Cost Benefit Analysis (CBA). LCA is (normally) by far the most comprehensive (all inclusive) of these.

1970s and 1980s – studies on beverage packaging

The first study considered to be an LCA was made in 1969-70 for Coca-Cola by Midwest Research Institute in the US. This was one of several studies on packaging and waste. The question was which is better to manufacture and use: beverage (steel or aluminium) cans, plastic bottles, refillable glass bottles or disposable containers. Coca-Cola asked for an all inclusive study of the energy, material and environmental costs of the entire chain from resource extraction to manufacture, use and finally waste of the containers. The researchers conducted a so-called Resource and Environmental Profile Analysis (REPA) for all the alternatives.

The first European study was done by Ian Boustedt at the Open University in the UK in 1972. Inspired by the Coca-Cola study and its development he constructed a case on milk bottles to be used in a text book. The work fitted well with the at times rather heated public debate on the pros and cons of returnable and non-returnable bottles for milk, beer etc. Later in the 1970s a German study was done on meat trays, and in Sweden on PVC bottles for Tetrapak, a very large company producing containers for beverages. The result came out in 1973, at the time when plastic bottles could be incinerated in the first waste incineration plants (in Malmö) and the impact of HCl, produced in the incineration, could be estimated.

The 1990s - LCA methodology develops

In the coming several years hundreds of similar studies were published, especial in the USA, UK, Germany and Sweden. Most often the databases used were made public, which was very important for the possibility of conducting more studies. In the mid 1980s first Switzerland, completed in 1990, and later Denmark and Sweden published very large packaging studies, in early 1990 and 1991. These early studies were mainly concerned with the energy and material used and waste released during the life cycle. It was not until later that the impact assessment was included in a more serious manner.

The first scientific conference on LCA was organised by the Society of Environmental Toxicology and Chemistry (SETAC) in 1991. Methodology was a main topic to discuss. Especially the reporting of environmental impacts was rather simple. Working groups were organised to develop recommendations for industry. LCA of products was now considered a more important tool for environmental improvement than just minimising the emissions from production. The main impact may be elsewhere, not least in the waste phase.

Into the 2000s
– Standardisations and Code of Practices

Efforts were made to make LCA data publicly available and to develop software for calculations. There were also strong forces requiring a standardisation of the methodology to make different studies comparable, especially to make it less easy to use LCA for promoting specific products. The first Code of Practice for LCA was published by SETAC in 1993. This work on methodology, especially concerning impact assessment, is still ongoing. The ISO standards for LCA have been published since 1997 (ISO 14040) and later 1998, 2000 and 2002. In 2005 the European Commission introduced its European Platform on Life Cycle Assessment as a component in the IPP Directive. Its initial phase, 2005 to 2008, intends to reduce costs for LCA studies, to harmonise quality control, and to produce consistent data basis. The intention is to establish LCA as a reliable support in decision making and promote its acceptance in governments.

Source: Baumann and Tillman, 2004.

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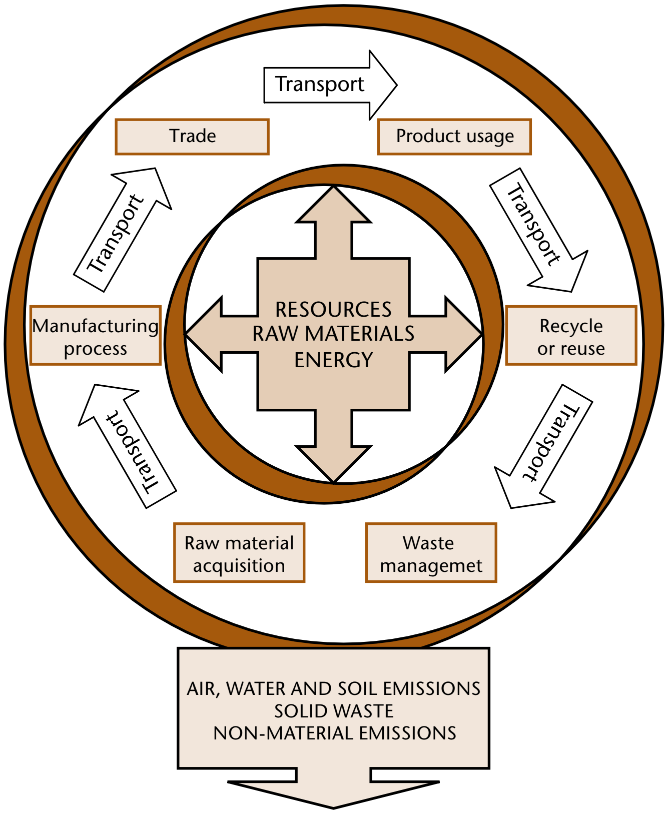

Figure 5.1 *Product life cycle [Stachowicz, 2001; Walz, 2000].*

5.1.4 Developments of LCA

There are many shortcomings in the applications of LCA techniques. Up to the present time, the main focus of research in LCA has been on developing LCA as a tool rather than a system [Hauschild and Wenzel, 1998]. Hence, there has been an emphasis upon assessment of potential environmental effects. Relatively little attention has been paid to, for example, the process of defining alternatives for consideration in an LCA, or choice of weighting factors. Further research could allow us to develop LCA as a system capable of assessing the environmental impact per function, system needed or money spent. Such a new approach would allow us to *search for conditions for reaching maximum cost-effectiveness* with respect to the environment for a function or product. Then the ratio of system cost/environmental impact could be maximized. A method to do this will be discussed later, primarily developed and tested to support Life Cycle Management (LCM) of capital assets [Stavenuiter, 2002].

Today's LCA approaches are valid *only for incremental changes in the product* of interest and *defined geopolitical regions*. To use LCA to provide answers to long-term planning issues is more difficult. Radical changes in technologies, legislative constraints or policy goals need to be anticipated. Future developments of key technologies and entire economic sectors will thus affect the outcome of the LCA. They have to be defined carefully [Frischknecht, 1997].

Current LCA integrates over time and space. A desegration of these two parameters are needed to get a more precise result. First *environmental impact is depending on location*. For example acidification is very different in different places. Desegregation of the inventory of impact as to location is a matter of practicability. It has been done in several studies, to allow for a differentiated impact assessment.

Desegregation in time is needed to allow for a differentiated impact assessment. One reason for “flattening out time” in current practice is that LCA is supposed to support decision making and affect future decisions, while for an actual system a substantial part of the processes have already taken place. For example, the factory which is bringing out a new car next year will itself have been set up some 10 years ago. The decisions in car design will not influence past decisions but only exert influences on production facilities yet to be built.

5.2 The Qualitative (approximate) LCA

5.2.1 The Red Flag Method

Qualitative LCA methods do not use systematic computational procedures to assess the environmental profile of the system under study. They analyse the life cycle of a product in environmental terms directly on the basis of emissions released and the consumption of raw materials. Assessing the seriousness of the impacts directly from the impact table requires thorough training and extensive knowledge. A decisive role is played by relevant experiences of the expert carrying out the evaluation.

The *red flag method* (RFM) may serve as an example of a qualitative method. There are a number of companies working with RFM, for instance Philips. The first step is, as usual, preparing an impact table. This gathers all emissions and material consumption during the whole life cycle of a product. Then, the items which are harmful to the environment are red-flagged. Red flags can occur along with emissions of CFCs (chlorofluorocarbons), toxic substances, greenhouse gases, etc. or where scarce materials are consumed. The red-flagged process or product should then be given special attention and if possible excluded from the life cycle of the product. Even though this approach is fairly easy, there is a major obstacle. The red flags many times are placed in nearly each process or life stage without, any distinction between small and large quantities of unwanted emissions. In practice not all these stages can be removed or changed. In these cases the red flag method does not provide a sufficiently qualified evaluation and is not useful.

A piece of the impact table for production of 1kg of EPDM rubber with flags is shown in Table 5.1.

5.2.2 The MET Matrix

Another qualitative method for assessing life cycle of a product is the so-called *MET matrix* (materials, energy and toxicity).

A MET analysis consists of five stages. The first is a discussion of the social relevance of the product's functions. Then the life cycle of the product under study is determined and all the relevant data is gathered. Next the data is used in which is the core of the MET matrix method: completing the matrix (Table 3.1). The processes in the life cycle are then entered in the matrix divided into three categories: material consumption, energy consumption, and emissions of toxic substances. As in the case of Red Flag Method, completion of the MET matrix can be done only with an aid of environmental experts. Finally, when the most significant environmental problems are identified, possible steps to improvement of the product or service should be outlined.

The qualitative methods in general have poor reproducibility. The reason is that they require support provided by experienced environmental experts, and that experts often come to different conclusions. The scientific support for making reproducible and reliable judgements is so far lacking.

Table 5.1 *Impact for production of 1kg of EPDM rubber.*

No	Substance	Compartment	Unit	Amount
1	Baryte	Raw materials	g	7.07
2	Nickel ⚐	Raw materials	mg	23.9
3	Sand	Raw materials	g	4.39
4	Acetone ⚐	Air emissions	µg	954
5	Cd ⚐	Air emissions	µg	978
6	He	Air emissions	mg	110
7	Methane ⚐	Air emissions	g	9.94
8	As ⚐	Water emissions	mg	1.24
9	K	Water emissions	mg	555
10	Na	Water emissions	g	26.5
11	Cr ⚐	Soil emissions	µg	460
12	Oil biodegradable	Soil emissions	µg	72.6

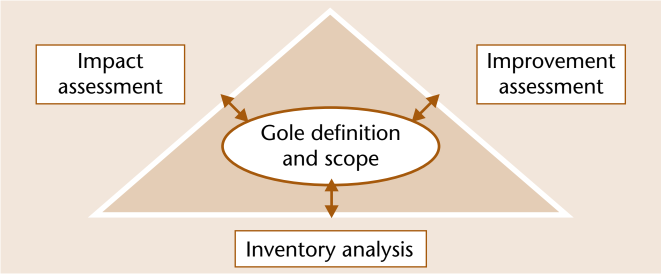

Figure 5.2 *Interrelation of LCA phases [Hillary, 1995].*

5.3 Quantitative LCA Methods

5.3.1 The Components of Quantitative Methods

There are a number of different quantitative LCA techniques. These are in practice applied as a group of methods which use classification, characterisation, normalisation and weighting. The most important are:

- Eco-points
- Eco-indicator
- EPS system
- MIPS concept

The methodological framework of all the LCA techniques is based on ISO standards 14040-43.

A complete LCA consistent with ISO standards consists of four interrelated phases (compare with the definition of LCA given by ISO):

1. *Goal definition and scope.*
2. *Inventory analysis.*
3. *Impact assessment* with four sub-phases: classification, characterisation, normalisation, weighting.
4. *Improvement assessment.*

Interrelations among the LCA phases make LCA an iterative process (Figure 5.2), [Hillary, 1995]. The calculation and evaluation procedure is repeated until the analysis reaches the required level of detail and reliability.

The first step in an LCA is a raw assessment to determine critical points in the life cycle and find directions for further studies. Such a quick analysis is called *screening*. Sometimes it is enough to answer all the questions asked in the goal definition.

Goal definition and scope is crucial for all the other phases. These include gathering data, that is building a model of the life cycle, choosing appropriate environmental effects to consider (local, global?), and drawing conclusions to answer the questions asked at the beginning of the project. Nevertheless, sometimes a previously established goal of the study needs to be changed to some extent, for instance when unforeseen obstacles arise (insufficient or unavailable data) or additional information arrives.

The last step, the *improvement assessment phase*, is performed in accordance with the goal of the study and on the basis of results from the impact assessment phase. This, in turn, is achieved by applying the computational procedure to the data in the inventory table.

5.3.2 Goal Definition and Scope

In the *goal definition and scope phase* the unambiguous and clear description of the goal of the study and its scope must be developed. The product (or service) to be assessed is defined, a functional basis for comparison in case of comparative analysis is chosen and, in general, the questions to be answered are established. The scope of the study sets requirements to the desirable level of detail.

The main issues to consider in this stage are:

- Purpose of the study: Why is the analysis being performed? What is the end use of the LCA? To whom are the results addressed?
- Specify the product to be investigated (functional unit).
- Scope of the study: depth and breadth (system boundaries).

As far as the *LCA end use* is concerned there are several basic possibilities:

- Product or process improvement.
- Product or process design.
- Publication of information on the product.
- Granting of an eco-label.
- Exclusion or admission of products from or to the market.
- Formulation of company policy (purchasing, waste management, product range, how to invest the money).

The intended audience is especially important to consider when preparing the presentation and communication of results. An LCA may be addressed to scientists, environmentalists, NGOs, the public (media, consumers). The manner of presenting the results should be tailored to meet their needs.

5.3.3 The Functional Unit

An LCA of a product must have *clearly specified functions* to be assessed. If, for instance, the product is a washing machine, it is important to describe its performance characteristics. These state what minimum quality standards the washing machine must meet: the degree of cleanliness and the degree to which clothes should be dried, how long the machine should work and how frequently it is to be used, the amount of clothes that can be washed at one time, etc. That is, it is important to define a function of a product rather than a product itself. The measure of performance which the system delivers is called a functional unit. The functional unit provides a reasonable point of reference when comparing different products.

Two products, A and B, may have different performance characteristics even though they fulfil the same function. An illustrative example is the comparison of different kinds of milk packaging, already discussed above. Two possible alternatives are: a milk carton and a returnable glass bottle. A glass bottle can be used ten or more times, whereas a milk carton can be used only once. On the other hand, a milk carton does not need washing and additional transportation. When comparing one carton and one bottle we could conclude that carton is the environmentally best choice. If the functional unit of the two packages is established, however, the analysis are not distorted by unfair assumptions.

Considered for example, that the packaging for 10 litres of milk could be a functional unit. In this case we have to com-

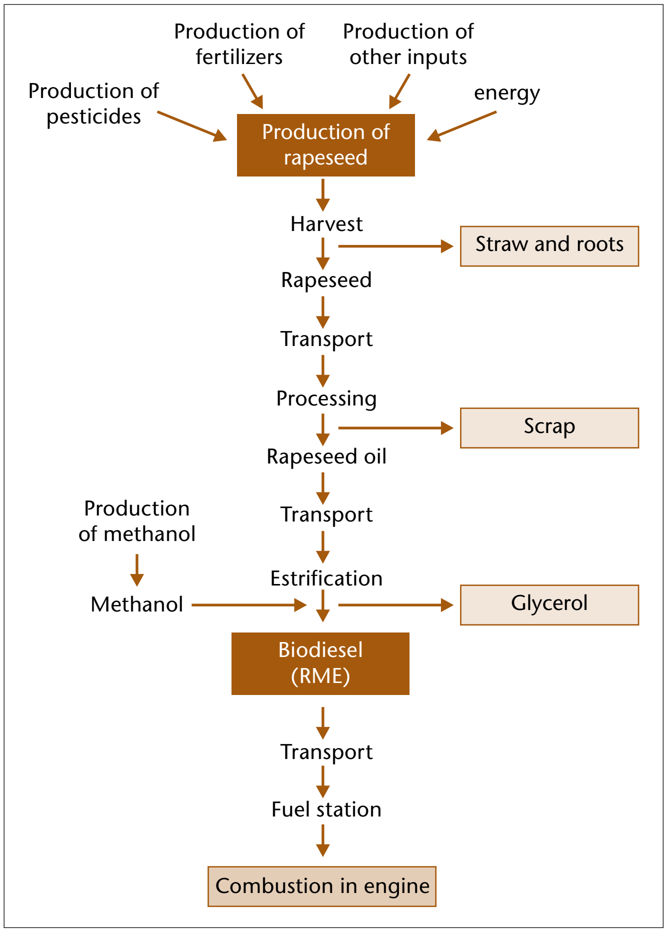

Figure 5.3 *Process tree of the production and use of biodiesel [Hillary, 1995].*

pare 10 milk cartons to 1 bottle and 9 washings (assuming 9 return trips of the bottle).

Another example of a functional unit is when one wish to compare different anti-corrosive paints used for protecting a metal surface. The functional unit in this case might be the amount of paint which covers a certain surface for a certain time , e.g. 1 m^2 painted for 2 years. We then compare the different properties of the paints, the lifetime of coating, and the ability to cover a specified surface instead of the amount of paint.

5.3.4 System Boundaries

The next vital task in the goal and scope definition step is to define *system boundaries*. The necessity of defining system boundaries results from the fact that the main technique applied in any LCA is *modelling*. A function fulfilled by the product is represented by a model of the complex technical system. This consists of subsequent processes required to produce, transport, use and dispose of a product. The model is graphically illustrated by a process tree (a process flow chart) (Figure 5.3) and is used in the inventory analysis. Moreover, models of environmental mechanisms are created to translate inflows and outflows from the life cycle into the environmental impacts they may contribute to. For example, SO_2 emissions could increase acidity. This, in turn, can cause soil and water impairment, influence the quality of the ecosystem, deteriorate the living condition for animals and plants, etc. Such models are the basis for the impact assessment phase.

A model, by its definition, is a representation of reality but at the same time it is a simplification of reality. It means that the reality must be distorted to some extent in a model. On the other hand, one cannot avoid this problem. The system without simplifications is too complex to analyse. If a product system should include all the processes “from cradle-to-grave” one has to follow each inflow or outflow. This include, for example, crude oil, solar energy, iron ore from the environment, and all final waste released to the environment, i.e. emissions to air, water, soil, radiation. As a result the process tree would be practically endlessly branched.

Product systems are usually interconnected in a complex way, and it is impossible to isolate a single life cycle of a product without coming up against life cycles of other products. Thus e.g. in an LCA on glass bottles, trucks are used for transportation, so life cycle of a truck should be involved into the LCA. In the life cycle of the truck, steel is used to produce many parts of the vehicle, coal is needed to produce steel, steel is transported by trucks, etc.

This phenomenon is called *endless regression*.

To avoid such a problem the boundaries of the system must be defined. The system under study has to be separated from the environment as well as from other products and systems.

The typical question when defining the system boundaries is whether to include *the production of capital goods* or not. In a majority of LCAs capital goods, e.g. equipment of a workshop, are neglected. This assumption does not lead to important distortions of the final LCA outcome. In some cases, however, neglecting capital goods significantly underestimates environmental burdens. This applies to, for example, electricity production. It has been shown, that the production of capital goods constitutes about 30% of the total environmental impact resulting from an average generation of electricity.

Another common problem is presented by agricultural areas, which can be seen as a part of nature or as a part of the production system. For instance pesticides can be treated as emissions if agricultural areas are a part of nature. Otherwise (when agricultural areas are seen as a part of an economic system) only the part of pesticides, which leaves, a field somehow (evaporate or are accidentally sprayed outside) are perceived as emissions. The rest, which are not released to the environment, remains a part of a system.

A similar problem – which substances should leave the life cycle – concerns dumping waste. It can be regarded as final waste released to the environment or the start for long-term waste processing.

To narrow down the system boundaries, one uses *cut-off rules*. Thus if the mass or economic value of the inflow is lower than a certain percentage (a previously set threshold) of the total inflow it is excluded from further analysis. The same applies when the contribution from an inflow to the environmental load is below a certain percentage of the total inflow.

Carefully and properly specified goals and scope help to develop the model of the product in such a way that the simplifications and thus distortions have only an insignificant influence on the results. This is vital for getting reliable answers from an LCA. This challenging task undoubtedly depends to some degree on subjective decisions and requires a lot of experience.

5.4 Inventory Analysis and Allocation

5.4.1 Inventory Table

The inventory phase is the core of an LCA and is a common feature of any LCA. During this phase all the material flows, the energy flows and all the waste streams released to the environment over the whole life cycle of the system under study are identified and quantified. The final result of the inventory analysis is an inventory table. The inventory phase has four separate sub-stages:

- Constructing a process flow chart (so-called process tree).
- Collecting the data.
- Relating the data to a chosen functional unit (allocation).
- Developing an overall energy and material balance (all inputs and outputs from the entire life cycle) – an inventory table.

To develop a life cycle it is best to start from the product itself and then follow all upstream and downstream life stages. This makes the LCA work systematic. Possible *upstream stages* are: extraction and production of raw materials, production of components (intermediates, semi-finished products, different parts), production of auxiliary materials (such as solvents, catalysts, etc.) and eventually production of the product itself. Among *downstream stages* are: use of the product, waste handling, processes of recycling and reuse if needed. Additionally, between all these processes, usually transport is needed and similarly the production of the energy carriers (electricity, steam) occurs along with almost all processes and life stages. A result of this step is illustrated by the process tree of the production of biodiesel (Figure 5.3), [Hillary, 1995].

Table 5.2 *Selected items in an inventory table for the production of 1 kg of PVC derived from SimaPro.*

No	Substance	Compartment	Unit	Total
1	Air	Raw material	g	220
2	Barrage water	Raw material	kg	99
3	Baryte	Raw material	mg	82
4	Bauxite	Raw material	mg	440
5	Bentomite	Raw material	mg	32
6	Clay minerals	Raw material	mg	9
7	Coal	Raw material	g	135
8	Crude oil IDEMAT	Raw material	g	400
9	Dolomite	Raw material	mg	2
10	Energy (undefined)	Raw material	MJ	113
⋮				
22	Cl_2	Air	mg	2
23	CO	Air	g	2.3
24	CO_2	Air	kg	2
25	C_xH_y	Air	g	19
26	Dust	Air	g	29
⋮				
36	Acid as H^+	Wastewater	mg	48
37	BOD	Wastewater	mg	850
38	Calcium ions	Wastewater	mg	47
39	Cl	Wastewater	g	37
40	COD	Wastewater	mg	76
41	C_xH_y	Wastewater	mg	26
42	Detergent/oil	Wastewater	mg	49
⋮				
60	Mineral waste	Solid waste	g	42
61	Plastic production waste	Solid waste	mg	440
62	Slag	Solid waste	g	9.4
63	Unspecified	Solid waste	mg	9
64	Occupied area as industrial area	Non material (land use)	m^2	400

On the basis of such a process tree, more detailed data is collected as required by the previously defined goal and scope (required level of details). All these actions have the same goal, namely to obtain a list of all inputs (materials consumed) and outputs (emissions) connected with the life cycle of the product. The data should be quantitative and are used to build an *inventory table*. An example of an inventory table for production of PVC is shown in Table 5.2. Note that this example of an inventory table is significantly abridged (it contains 27 out of 64 items).

To obtain such a table one should link the data describing the processes involved to produce the functional unit (e.g. how much CO_2 is released in conjunction with the production of 10 milk cartons).

5.4.2 Allocation

Very often a process fulfils two or more functions or gives two or several of usable outputs. They are *multi-output processes*. Then we have to determine which part of the total emissions and material consumption should be attributed to each specific product. The same applies to *multi-input processes*. Petrol production can serve as an example of a multi-output process. It provides several products in fractional distillation of crude oil: not only petrol but also kerosene, diesel oil, and mazout. The question is how to divide emissions and resource consumption over the petrol itself. An example of a multi-input process is a plastic bag. When performing an LCA for a plastic bag, we assume that at the end of its life cycle it is incinerated. However, there are many other products incinerated at one time. To what extent is the bag responsible for chemicals emitted from the incineration plant?

The problem of how to divide emissions and material consumption between several product or processes is called *allocation*. Several methods have been developed to deal with allocation.

Substitution of allocation – no allocation in fact. As allocation always require more or less subjective decisions, ISO recommends to avoid allocation if possible. This can be done by extending the system boundaries i.e. by including processes that would be needed to make the same by-product in the conventional way.

As an example, we can imagine a process in which a usable quantity of steam is produced as an additional output. It can be used to avoid the production of steam by more conventional means. This is an additional gain resulting from the process associated with the analysed product. This fact should be reflected in the main product's environmental profile. Then the environmental load of the avoided steam production may be subtracted from the overall environmental burden of the process. In this way one can calculate the part of emissions and material consumption that the main product is responsible for, and the rest is ascribed to the steam. The material consumed and emissions released, from the traditional way of producing steam are subtracted. It is not always easy to say how the steam would be produced alternatively, i.e. what a conventional method of steam production actually is.

Another typical example is electricity production in conjunction with waste incineration. The main purpose of this process is waste utilisation, but the simultaneously generated electricity is an additional benefit.

Allocation based on natural causality – in other words depending on one's common sense. In cases of combined waste incineration, SO_x emissions should be allocated in relation to the S-content of different products, i.e. the more sulphur a certain product contains the more it is responsible for emissions of sulphur oxides. If a fraction of waste does not contain any sulphur, one may say it is not responsible for releasing sulphur oxides. Regrettably, there are plenty of examples of allocation problems, which this principle cannot solve.

Allocation based on physical parameters such as mass, energy, etc. Let us consider two usable products in a sawmill: wooden boards, as a main product, and sawdust as a by-product. When performing an LCA of wooden boards, an allocation problem will arise. An appropriate part of the environmental impact of the boards themselves can be derived directly from mass balance between outputs. If, for example, 40% of the total mass of the wood processed gives the sawdust, one can ascribe 40% of the environmental load to sawdust. Another example is naphtha cracking. Note that if this rule were applied in case of allocating steam, it would lead to ambiguous results since the mass of the steam is incomparably smaller.

Allocation based on economic values (prices). This principle is analogous to the previous one except that here economic values are the criteria. If, in the example of the sawmill, the sawdust contributes 20% of the value generated by the sawmill, one can allocate 20% of the environmental load to this by-product. Usually the main product is the most valuable, and has the highest price. By applying this method, the product for which the process is carried out is the most responsible for the total environmental burden. Prices, however, tend to change in time. Consequently the economic situation may influence an LCA although the environmental profile of a process itself remains the same.

Arbitrary allocation. The contribution of each co-product in the overall emissions and material consumption can be also imposed arbitrarily, e.g. equally for each product, 100% of emissions to one product, or any other random distribution.

Allocation Techniques

- Substitution of allocation.
- Natural causality allocation.
- Allocation based on physical parameters.
- Allocation based on economic values.
- Arbitrary allocation.

Study Questions

1. Give your own definition of LCA.
2. For what is LCA needed?
3. Which are the differences between quantitative and qualitative LCA methods.
4. What is a goal definition and scope of an LCA?
5. How should you define a functional unit? Will we obtain the same LCA results for product treated as different functional units? Give examples.
6. Which are the difficulties to decide on systems boundaries? Give example of cut off rules.
7. Define system boundaries for a simple product.
8. Write a simple process tree.
9. Which are the methods for allocation, both upstream and downstream?
10. Make an inventory analysis for a spoonful of tea.

Abbreviations

CBA	Cost Benefit Analysis.
EIA	Environmental Impact Assessment.
EM	Environmental Management.
EPS	Environmental Priority Strategies.
ERA	Ecological Risk Assessment.
LCA	Life Cycle Assessment.
LCM	Life Cycle Management.
MET	Materials Energy Toxicity.
MFA	Material Flows Analysis.
MIPS	Material Input Per Service unit.
NGO	Non Governmental Organisations.
RFM	Red Flag Method.

Internet Resources

Society of Environmental Toxicology and Chemistry

www.setac.org; http://www.setac.org/htdocs/who_intgrp_lca.html

ISO organisation

http://www.iso.org/

PRé Consultants Life Cycle Assessment

http://www.pre.nl/life_cycle_assessment/default.htm

US Environmental Protection Agency
Life-Cycle Assessment – LCAccess

http://www.epa.gov/ORD/NRMRL/lcaccess

Life Cycle Assessment Links

http://www.life-cycle.org/

UNEP environmental management tools Life-Cycle Assessment

http://www.uneptie.org/pc/pc/tools/lca.htm

European Environment Agency's guide to approaches, experiences and information sources of LCA

http://reports.eea.eu.int/GH-07-97-595-EN-C/en