LIFE CYCLE ASSESSMENT

1. Introduction

Environmental policy today focuses on the transition to sustainable production and consumption patterns. This transition is taking place in various ways and at various levels. Knowledge of the environmental impact of production and consumption patterns is indispensable for improving the performance of industries and consumers in this area. Integrated assessment of all environmental impacts, from beginning to end is the basis for achieving more sustainable products and services. One of the assessment tools widely used for this is environmental Life Cycle Assessment (LCA). One of LCA's Leitmotivs is to get a full picture of a product's impacts in order to find the best solutions for their improvement without shifting the impact to other fields.

Life cycle assessment has become a core topic in the field of environmental management. The International Organization for Standardization (ISO) has played and still is playing a role in the task of methodology standardization. Within the ISO 14040 series, several international standards have been published by ISO on the topic of LCA. The central main series is ISO 14040 (1): "Environmental management—Life Cycle Assessment—Principles and framework": which specifies the main ideas of LCA. These ideas have been elaborated in other international standards and technical reports, eg, ISO 14041 (2), 14042 (3), and 14043 (4). These standards are currently under revision and will be replaced by a new single document, ISO 14044, which only includes editorial changes, but no changes with respect to technical content.

According to ISO 14040, LCA is a "compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system throughout its life cycle". Moreover, it is stated that "A product system is a collection of unit processes connected by flows of intermediate products which perform one or more defined functions. [...] The essential property of a product system is characterized by its function, and cannot be defined solely in terms of the final products". Products include goods and services providing a given function. Next, a product is discussed as being a part taken as a whole for all objects of LCA, if they are not specified otherwise.

LCA begins with its function being fulfilled by a product system. In principle, it encompasses all the environmental impacts of resource use, land use, and emissions associated with all the processes required by this product system to fulfill this function—from resource extraction, through materials production and processing and use of the product during fulfillment of its function, to waste processing of the discarded product. Ultimately, this means that all environmental impacts are related to this function, which is the basis for comparisons to be made.

Life cycle assessment as defined here deals only with the environmental impacts of a product (system), thus ignoring financial, political, social, and other factors (eg, costs, regulatory matters, or Third World issues). This does not, of course, imply that these other aspects are less relevant for the overall evaluation of a product, but merely delimits the scope of LCA. In practice, LCA seldom deals with all environmental impacts, eg, biotic resources are often not included.

A prime purpose of LCA is to support the choice of different (technological) options for fulfilling a certain function by compiling and evaluating the environmental consequences of these options. It should indicate the effects of choices in a way that prevents problem shifting. Problem shifting can occur when analyzing only one activity, one area, one substance, one environmental problem, or effects over a limited period of time. So the LCA model tries to cover all activities related to a product or function; stating effects anywhere in the world; covering all relevant substances and environmental themes; and having a long-time horizon. This encompassing nature of LCA in place, time, and effect mechanisms has as a corollary that the model used should be relatively simple in order to keep the analysis feasible.

Doing LCA for a specific product or set of product alternatives requires several things:

1. Data on the production, use and disposal of the product that the materials are made from, the energy it requires, etc.
2. A method to combine all these data in the appropriate way.
3. Software, in which all these methodological rules have been implemented.
4. A procedural context in which the process of doing LCA and using its results is embedded.

In the following, the emphasis is on the method and is discussed. Aspects of data, software, and procedures are separately discussed later.

Besides a description of the state-of-the-art of LCA in terms of methods, data, software, and procedures, the practice of LCA is worth discussing as well. A final brief section therefore is devoted to case studies, the relation with life-cycle management, other tools for environmental decision support, and a future outlook.

2. The Method

The complexity of LCA requires a fixed protocol for performing an LCA study. Such a protocol has been established by the ISO and is generally referred to as the methodological framework. The ISO distinguishes four phases of an LCA study (see Fig. 1):

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

From Fig. 1, it is apparent that LCA is not a linear process, starting with the first and ending with the last phase. Instead, it follows an iterative procedure in which the level of detail may subsequently be increased. Despite its iterative character, most important methodological aspects of the different phases and steps within these phases will be discussed below in a sequential mode.

The ISO International Standards mentioned are important in providing an international reference with respect to principles, framework, and terminology for conducting and reporting LCA studies. The ISO standards do not, however, provide a step-by-step operational guideline for conducting an LCA study. Several guidebooks have been published to support the process of doing LCA with more concrete guidelines, decision trees, tables with conversion factors, and mathematical equations. Some key guidebooks are listed in Table 1.

2.1. Phase 1: Goal and Scope Definition. The goal and scope definition phase is the first phase of an LCA, and it establishes the goal of the intended study, the functional unit, the reference flow, the product system(s) under study, and the breadth and depth of the study in relation to this goal.

First, the goal of the study is stated and justified. The goal (aim or objective) is explained and the intended use of the results (application) are explained; the initiator (and commissioner) of the study; the practitioner; the stakeholders; and for whom the study results are intended (target audience).

Next, the main characteristics of an intended LCA study are established, covering such issues as temporal, geographical and technology coverage, the mode of analysis employed, and the overall level of sophistication of the study (scope definition). Two points need further explanation: The mode of analysis and the level of sophistication.

The main purpose of LCA, as stated above, leaves room for at least two quite distinct interpretations, or modes of analysis, of LCA. The first answers the question of accounting: What is the share or contribution of one particular way of fulfilling a certain function in the entire set of environmental problems that currently exist? When LCA is used to answer this question it is referred to as a descriptive LCA, and can be a starting point for an improvement analysis. The second interpretation puts an emphasis on change. The analysis then addresses the environmental implications of a change from or to one particular way of fulfilling a certain function. This change may assume many forms, which may be illustrated as “drinking one more beer” and “drinking a different brand of beer”. Within this so-called change-oriented LCA, we distinguish between three main types of questions, which are related to three main choices:

1. Occasional choices related to one-time functions or small-scale optimizations: eg, should I take the high speed train or the plane to my meeting in Paris next week?
2. Structural choices related to a function to be delivered regularly: eg, should I take the high speed train or the plane to my weekly meetings in Paris?
3. Strategic choices, binding the choice on how to supply a function for a long, or even indefinite period of time: eg, should the government invest in high speed railroads or in airports?

All three questions require their own modeling set-up. In most guidebooks on LCA, the focus is on structural choices. The approaches that have been developed by Azapagic (16) and by Weidema and co-workers (17) may be particularly useful for LCAs with occasional choices as a starting point.

There are various levels of sophistication of LCA possible. Two levels are often distinguished and sometimes elaborated in separate sets of guidelines (13): a simplified and a detailed level. The simplified level has been introduced for making faster and cheaper LCAs compared to detailed levels of LCAs. The guidelines for simplified LCA usually comply with the ISO standards. The guidelines given for detailed LCA fully comply with the various ISO Standards as mentioned. It is evident that the results of simplified analysis will generally be less certain and robust than those of detailed LCA.

A crucial element of the goal and scope definition phase concerns the definition of the function, functional unit, alternatives, and reference flows. The functional unit describes the primary function(s) fulfilled by a (product) system, and indicates how much of this function is to be considered in the intended LCA study. It will be used as a basis for selecting one or more alternative (product) systems that might provide these function(s). The functional unit enables different systems to be treated as functionally equivalent and allows reference flows to be determined for each of them. For example, one could define a functional unit for wall coloring in terms of the area to be covered, the type of wall, the ability of the paint to hide the underlying surface and its useful life. In a real example, then, the functional unit of a wall covering would be "20-m^2 wall covering with a thermal resistance of 2 m^2 K/W, with a colored surface of 98% opacity, not requiring any other coloring for 5 years" (18). In this functional unit, thermal resistance is included as a second function besides coloring. One can define the function of a given product system as precisely as one wishes. However, the more strictly the functional unit is described, the fewer alternatives will be left to compare.

On the basis of the functional unit, a number of alternative product systems may be declared functionally equivalent and reference flows will be determined for these systems. The reference flow is a measure of the needed outputs from processes in a given (product) system that are required to fulfill the function expressed by the functional unit. For example, the above functional unit for wall covering might be fulfilled by a 20-m^2 wall covered with paint A, which is therefore the reference flow for the product system that corresponds to paint A. Paint A might be compared to paint B providing the same coverage of the 20-m^2 wall, but requiring a different amount. For example, 10 L of paint A and 15 L of paint B might be needed to provide the specified function.

Note that no calculations are made and no data are collected in the goal and scope definition. It really is a place for initial reflection: What exactly will the calculations be about.

2.2. Phase 2: Inventory Analysis. In the inventory analysis, often referred to as LCI, the life cycle of the product (alternatives) analyzed is determined, first qualitatively and then quantitatively.

The basis of the inventory analysis is the unit process. This process is an elementary operation, like rolling of steel, the generation of electricity through coal gasification, playing of a CD, or the recycling of paper. The aggregation level of a unit process will differ in practice from LCA to LCA and even within one LCA. Sometimes a whole refinery is considered as a unit process, while in another study, such a refinery is stripped into 50 separate subprocesses. An average LCA may comprise ~50–500 unit processes. A number of unit processes linked together may constitute a system that can be assessed by LCA. The general structure of a unit process is shown in Figure 2. Four main groups of flows can be discerned.

1. Economic inflows (eg, the electricity and steel required for rolling steel).
2. Environmental (or elementary) inflows (eg, the ores and fossil fuels absorbed by a material production process).
3. Economic outflows, eg, the rolled steel produced by the process of rolling steel.
4. Environmental (or elementary) outflows (eg, the emissions to air and water by an industrial activity).

In the categorization of flows, one should observe that waste flows are economic flows. The meaning of the term "economic" has no connection with the value or price of the commodity, and neither does it point to the objective of a process. It only indicates that this flow connects two unit processes: It is an inflow for one process and an outflow for another. This finding is in contrast to the situation for environmental flows that are only connected to one unit process: Environmental inflows flow from the environment to the unit process, and environmental outflows flow from the unit process to the environment.

Before defining a system of unit processes, the system boundaries have to be defined between the product system (as part of the physical economy) and the environment. Or put in other terms: Which flows cross this boundary and are environmental interventions (ie, resources extractions, emissions, and land use) need to be defined. Forests and other biological production systems (see Fig. 3) are examples of confusion on this point. Do they belong to the environment and is wood a resource coming into the physical economy (natural forest)? Or is the forest already part of the economy, and are solar energy, carbondioxide, water, and minerals to be regarded as the environmental interventions passing the boundary between the environment and the economy (forestry)? Another example concerns the other end of the life cycle: Is a landfill to be regarded as part of the environment or is it still part of the physical economy? In the first case, all materials that are brought to the landfill have to be regarded as emissions into the environment; in the latter case, this will only hold for the emissions from the landfill to air and groundwater. In order to make the results of different studies comparable, there is a great need for harmonization. An element may well be the degree to which the processes involved are steered by human activities. Forestry can be regarded as part of the socioeconomic system, but wood extracted from a natural forest will have to be regarded as a critical resource taken from the environment. Likewise, a landfill, managed without any control measures, should be regarded as part of the environment, with all discarded materials regarded as emissions. If the landfill is a well-controlled site, which is separated from groundwater and cleans of the percolation water, it may be regarded as part of the product system with only the emissions from the landfill considered as burdens to the environment. Clear guidelines for including processes within the system are available: landfill and forestry should be included. Nevertheless, one should be aware of specific details that may differ from study to study, eg, the depth of the (agricultural) soil demarcating which part is included and which is not.

The next step concerns drawing the flow diagram of the system studied. It constitutes the basis for the whole analysis and identifies all relevant processes of the product system with their interconnections. The functional unit delivered by the system is the central element; starting from here, the processes ramify "upstream" up to the different resources used, and "downstream" to the different ways of waste management involved. Figure 4 gives an example of a flow diagram. Here, boxes are unit processes and arrows are economic flows. The dashed lines indicate the system boundary chosen, namely, processes outside the dashed area are excluded from the analysis (see below under cut-off). A flow chart is supposed to illustrate the processes and their qualitative connections. The connections are the economic flows. To keep the flow chart focused and readable, environmental flows and quantitative information are often left out.

A flow diagram can become quite huge when applying the life cycle concept in a strict sense. In the refinery, much machinery needs to be cleaned and lubricated and require maintenance and replacement parts. In addition, offices and office equipment are needed. Intuitively, one would say that the impact of the office and office equipment will be negligible compared to the production of naphta and kerosene. In other words, the flow diagram might be cut off at several places. If all goes well, cut-offs are only made for processes that have a negligible contribution to the total impact. Extreme care should be taken when applying cut-offs.

By putting cut-offs in flow diagrams, the impact of the processes cut-off are no longer taken into account. A practical problem with this is that one cannot draw a flow diagram of 500 or more unit processes anymore. The key reason for making cut-offs in the quantification of impacts, however, is a lack of readily accessible data, implying disproportionate expenditure of funds and effort on data collection. Cut-off may substantially influence the outcome of an LCA study, however, and means that "easy" LCAs come at a price. Today, it is possible to better handle the cut-off problem by estimating the environmental interventions associated with flows for which no readily accessible data are available by using environmentally extended input–output analysis (19).

After the qualitative flow diagram, a quantification of the diagram follows. Data collection is a core issue in LCA and needs to be collected for each unit process of the flow diagram. These data concern all the categories of Figure 2. Generally, process characteristics are reported as averages (CO_2 emission/1000 MJ of electricity, iron used per ton of steel, etc). The number of process data can easily mount up to several hundreds or thousands.

There are several generic databases and references are available for supporting data collection (see section on Data), but for a specific case study it may also be very relevant to collect primary data for a number of processes.

For LCA models, like any other model, data quality may have a major influence on results and proper evaluation of data quality is therefore an important step in every LCA. The data used in a given case study should, eg, be representative for that particular study. Various partial methods are available for data quality assessment in LCA, but a generally agreed standardized method for overall assessment of data quality is lacking as yet.

In the quantification of processes, as described above, all processes are reported in their characteristic quantities. Subsequently, the processes must be scaled in the inventory analysis to the actual quantities needed for the product system studied: if 67 MJ instead of 1000 MJ of electricity is needed for that product system, all in- and outputs of that process need to be multiplied by 67/1000. The functional unit sets the conditions here: If the analysis is about painting 10 m^2 of wall for 10 years, this 100 $m^2 \times$ year determines how much paint, and thus how much electricity, and coal and CO_2 are related to that.

In scaling the process data to the actual quantities needed, the problem of multiple processes and allocation frequently comes up. As allocation is an important issue in the LCA debate, this issue will be discussed more extensively here. The problem lies in processes that are part of more than one product system, the so-called "multifunctional processes". How should the environmental impact of these processes be allocated to the different product systems involved? If a product, eg, contains polyvinyl chloride (PVC), chlorine is needed to produce the PVC. Chlorine is generally coproduced with caustic soda in one process. All other flows of this process (the sodium chloride input, the electricity use, the emissions) must be partitioned over the coproducts, namely, chlorine and caustic soda, in one way or another. This partitioning step is called allocation. The basis for allocation is debated intensively within the LCA community. Allocation is often done based on the relative mass, energy content, or economic value of the coproducts.

There are three basic types of multifunctional processes that require partitioning (Fig. 5): (*1*) multi-output processes (coproduction, eg, the chlorine and caustic soda production process); (*2*) multi-input processes (combined waste processing, eg, a waste incinerator incinerating various different waste flows simultaneously); and (*3*) recovery and recycling processes (where a waste flow is upgraded to a useful material).

Coproduction means that one unit process produces more than one functional output. The question is How should the environmental burdens (the environmental interventions from and to the environment) be allocated to these different functional outputs? Traditionally, this is done on a mass basis. But the example of diamond production that goes together with the production of a great bulk of stones as a by-product shows that this may not be equitable: All burdens would be allocated to the stones and not to the diamonds, although the latter are the reasons for the existence of the mine. Another principle concerns allocation on the basis of economic value, as the key steering factor for all production processes. Note that it is also an economic principle that determines what has to be allocated to what: As wastes have to be allocated to products, only an economic principle can decide which output is waste and which is product or by-product.

With combined waste treatment, the problem is that emissions from an incineration plant will contain a broad spectrum of materials, which will definitely not be included in much of the burned wastes. Allocating the emission of cadmium to the waste management of a polyethylene (PE) bottle again is not equitable. The procedure should begin here with a causality principle linking, as much as possible, materials to different fractions of the waste.

With recycling we can distinguish between closed- and open-loop situations. In a fully closed loop situation there is no allocation problem, because there is only one product at stake. Generally, loops will in part or in total be open: The wastes from one product system will be used as a secondary resource for another. In this situation, we deal with a multiple process for which an allocation rule has to be defined. Often, a "50% rule" is used, giving an equal share to the two product systems involved, but more sophisticated logic also may be applied. In addition to this, one may also want to allocate part of the resource needs for product system A to product system B, because the latter also makes use of the resources, and part of the wastes from product system B to product system A, because system B also solves the waste problem for system A.

The ISO (2) has proposed a preference order of different options to be checked on their applicability from one to the other. In short, this preference order consists of the following steps:

1. Allocation by dividing processes into subprocesses.
2. Allocation by expanding the boundaries of the system (*system expansion*).
3. Applying principles of physical causality for allocation of the burdens.
4. Applying other principles of causality, eg, economic values.

According to ISO (2), the first two options can be interpreted as avoiding allocation.

Although the different order options of this preference are clear, the practical implementation differs among practitioners. Some authors (20,21) have elaborated system expansion (also called "substitution", and "subtraction", and "avoided burden" methods) as an allocation method. The concept behind system expansion is that the production of a coproduct by a process causes another process for another product to be avoided. For example, if the production of chlorine also coproduces caustic soda, another process producing the same caustic soda needs to produce less caustic soda to fulfill the same demand of caustic soda. Therefore, it is argued that we may subtract the avoided emissions, resources, electricity use, etc, from the life cycle interventions of the product system for which the chlorine is needed. As in other allocation methods, problems rise when putting this method into practice. If a waste incinerator coproduces a certain amount of electricity, which type of electricity generation is then avoided? Electricity from natural gas, from uranium, from wind, or from a mixture of these?

Others (13,22) have elaborated economic allocation as a methodology that can be applied consistently for all types of allocation situations.

It must be stressed that such choices (partitioning versus system expansion, mass versus energy content versus economic value, electricity production from gas versus uranium versus wind) may significantly influence the results of a specific LCA study.

Ultimately, when all allocation issues are resolved and process data have been scaled to the actual quantities needed for the product system studies, all economic intermediary flows (paint, electricity, oil) are transposed into flows from and to the environment. The result is a potentially long list of resource extractions and emissions associated with a functional unit of the product studied. This list is often called the inventory table. An inventory table of 300 different substances is not unusual. In the computation process, care must be taken that loops of flows are taken into account properly; eg, electricity production requires steel and the production of steel requires electricity. Computational details are specified by Heijungs and Suh (23). In Table 2, the inventory results are shown for the hypothetical system of PE throw-away bags.

Apart from the quantitative entries, the inventory results may also include qualitative issues and flags, points that cannot be dealt with in a quantitative way, but that have to be considered in the final appraisal of the results.

At this time, the inventory analysis is the most time-consuming phase of an LCA due to the lack of readily available data. This situation may change in the near future as efforts continue to develop national and international databases. See Future of LCA for more discussion on data availability.

2.3. Phase 3: Impact Assessment. As discussed, the final result of the inventory analysis is a long list of resource extractions and emissions that can easily mount up to a couple of hundred entries. Comparing product alternatives and finding options of product improvements based on this long list is difficult, if not impossible. A further interpretation and aggregation of this list is therefore very desirable.

The basic idea is simple. The inventory table sometimes includes 10 or more heavy metals (lead, mercury, chromium, cadmium) and these are substances that are toxic at greater or lesser levels. In addition, the inventory may include a number of acidifying substances and a dozen CFCs known for their contribution to climate change impacts. Thus it seems obvious to sort together all substances that contribute to a particular type of environmental impact, and to aggregate substances within such an impact type according to their toxicity, acidifying potential, etc.

The impact assessment phase (see Phase 3: Impact Assessment) often referred to as LCIA, deals with this topic. According to ISO 14040, impact assessment is a “phase of LCA aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of the product system”. Within the impact assessment phase, several steps may be distinguished:

1. Selection of impact categories.
2. Selection of characterization methods: category indicators, characterization models, and factors.
3. Classification (assignment of inventory results to impact categories).
4. Characterization.
5. Normalization.
6. Grouping.
7. Weighting.

According to ISO, the first four steps are mandatory and the last three are optional.

In step 1, relevant impact categories are defined. There are various ways to do this. Some consider toxicity, eg, as an impact category, while others will split this category up into carcinogenity, mutagenity, neurotoxicity, allergenity, and many other possible toxic impacts. It is clear that the first approach will result in a shorter list of impact categories than the second approach, but the results of the first approach are subject to more debate. After all, combining allergic reactions and life-shortening diseases often includes an explicit or implicit weighting of the relative seriousness of allergies compared to, eg, cancer. Nevertheless, the first approach, drastic aggregation of inventory results to 10–15 impact categories, is currently dominant. Even more drastic approaches have already been developed, which aggregate inventory results into three impact categories: human health, ecosystem health, and resources (24–26).

The following list illustrates which impact categories are typically addressed in an LCA:

1. Depletion of resources (eg, subdivided into abiotic and biotic).
2. Desiccation.
3. Impacts of land use (eg, subdivided into land competition, loss of life support functions, loss of biodiversity).
4. Climate change.
5. Stratospheric ozone depletion.
6. Human toxicity.
7. Ecotoxicity (sometimes subdivided into freshwater aquatic, marine aquatic, terrestrial).
8. Photooxidant formation.
9. Acidification.
10. Eutrophication.
11. Impacts of ionising radiation.
12. Odor.
13. Noise.
14. Waste heat.

This list is based on a so-called midpoint approach. The methods proposed by Hofstetter (24), Goedkoop and Spriensma (25), and Steen (26) are often called endpoint-oriented approaches. The key difference between midpoint and endpoint approaches is the point in the environmental mechanism [ie, the chain of environmental processes linking interventions to impacts; modeled in LCA (usually only partially) to one or more category endpoints by means of a characterization model] at which the category indicators are defined. They may be defined close to the intervention (the midpoint or problem-oriented approach), or they may be defined at the level of category endpoints (the endpoint or damage approach).

Energy use is sometimes also mentioned as an impact category. However, in LCA the focus is on the impacts that are the consequence of the production and use of energy, eg, electricity, due to emissions (CO_2, SO_2, PAHs) and resource use (coal, gas, oil). The same reasoning applies to waste (in kg or m^3) as a separate impact category: In LCA the focus is on impacts that are the consequence of waste management processes, be it landfill, incineration, etc, and not the inflow stream of waste to be processed by these techniques. Some of these categories are not yet calculated, particularly due to a lack of (proper) data and/or methods. This finding is particularly true for radiation, horizon pollution, warming of river water through waste heat, and land use.

Subsequently, the interventions recorded in the inventory table are quantified in terms of a common category indicator. To this end characterization models are used, from which characterization factors are derived for individual pollutants, etc. The factors translating emissions into contributions to impact categories are called characterization factors. These are often based on complex environmental models comprising transport processes through the environment, degradation, intake, and the impact of substances. For each impact category listed in above, a characterization method comprising a category indicator, a characterization model, and characterization factors derived from the model should thus be available or developed. For the impact category climate change, a characterization method may resemble the example given in Table 3.

Examples of characterization factors and models for a number of baseline impact categories are listed in Table 4.

Today it is generally recognized that characterization methods for assessing chemical releases should include a measure of both fate (including exposure/intake where relevant) and effect of the substances. The fate aspect involves the distribution over and persistence within the different environmental media. For toxic releases, fate may be modeled by, eg, multimedia models and effect may be expressed by, eg, a so-called PNEC (Predicted No-Effect Concentration) or similar effect indicator.

Most characterization methods are globally oriented, but of course, refinements are possible here. This is not necessary for global categories, including the two mentioned above, but may be relevant for categories like acidification and eutrophication. Another refinement concerns the possible inclusion of anthropogenic background levels. This may, eg, be relevant for the assessment of toxic releases and is already used in the assessment of photooxidant forming releases.

Note, however, that characterization modeling is by no means without obstacles. Due to the fact that many categories are quite heterogeneous with respect to their underlying mechanisms, such characterization models (and their derived factors) cannot be defined on the basis of scientific knowledge alone, but will, to a smaller or larger extent, also be based on value judgments. In fact, this is also the case (although to a minor degree) with the well-accepted global warming models and GWP values (27).

In the classification step, the environmental interventions qualified and quantified in the Inventory analysis are assigned on a purely qualitative basis to the various preselected impact categories. Thus, CH_4 and CO_2 are, eg, assigned to climate change. A possible double counting may occur, eg, for a chemical like NO_x, that reacts to contribute to acidification and is then not available to cause toxic impacts.

In the characterization step, the environmental interventions assigned qualitatively to a particular impact category in classification are quantified in terms of a common unit for that category by their respective characterization factors, allowing aggregation into a single number: the indicator result. The resulting number for one particular impact category is referred to as a category indicator result, and the complete set of category indicator results as the environmental profile. For example, if the global warming potential for time horizon 100 years (GWP_{100}) of $CO_2 = 1$ and the GWP_{100} of $CH_4 = 21$, the indicator result for an emission of 2-kg CO_2 and an emission of 3-kg CH_4 for climate change using the GWP_{100} characterization factors becomes:

$$1 \times 2 + 21 \times 3 = 65 - \text{kg } CO_2 - \text{equiv.}$$

In Table 5, the environmental profile is shown for the hypothetical system of PE throw-away bags.

The indicator results are each expressed in their own units (eg, kg climate change equiv., kg 1,4-DCB equiv., etc). A further weighting of these scores is thus difficult without a prior processing, the so-called normalization. Normalization is an optional step of Impact assessment in which the indicator results are expressed relative to well-defined reference information. The reference information may relate to a given community (eg, The Netherlands, Europe, or the world), person (eg, a Danish citizen) (12), or other system, over a given period of time. Other reference information may also be adopted, of course, such as a future target situation. Every indicator result is thus expressed as a contribution to the total environmental problem for a given year and a given geographic area (eg, 1999 for the Netherlands). In this way, one may encounter a contribution of 10^{-12} by a certain product to the total acidification problem in The Netherlands in 1999, and 10^{-9} to smog. These numbers have no absolute meaning and can be rescaled to other metrics and scales (see above).

The aim of normalizing the category indicator results is to better understand the relative importance and magnitude of these results for each product system under study, providing information on the relative significance of the category indicator findings. Normalization can also be used to check for inconsistencies. In Table 6, the normalized environmental profile is shown for the hypothetical system of PE throw-away bags.

Grouping is another optional step of impact assessment in which impact categories are aggregated in one or more sets defined in the goal and scope definition phase. It may take the form of sorting, whereby impact categories are sorted on a nominal basis (eg, by characteristics such as emissions and resource use, or global, regional and local spatial scales) and/or ranking (whereby impact categories are hierarchically ranked (eg, high, medium, and low priority), applying value choices. Little work has yet been done on making this step operational (28).

A last optional step of impact assessment is weighting, where the (normalized) indicator results for each impact category assessed are assigned numerical factors according to their relative importance, multiplied by these factors, and possibly aggregated. This may include a formalized weighting procedure, resulting in one environmental index. The weighting can be done case by case, or on the basis of a generally applicable set of weighting factors. For the latter, three different lines can be distinguished, which are in part interconnected and may to some extent be combined: a monetary approach, in which a translation into monetary values is being performed; a distance-to-target approach, in which the weighting factors are in some way related to given reference levels; and a societal approach, in which the weighting factors are set in an authoritative procedure, comparable to the setting of standards. Although all steps of LCA contain value choices, weighting par excellence is based on value choices. The weighting factors are highly subjective as they are based on perceptions of what is worse: dead forests or dead fish, etc. Therefore, ISO 14042 (3) states that "weighting shall not be used for comparative assertions disclosed to the public". Outside ISO, however, weighting methods have received extensive attention since 1992. For an overview, see FINNVEDEN (29).

In Table 7, weighting results using a further unspecified weighting method are shown for the hypothetical system of PE throw-away bags. Note that the weighting factors in this example are purely fictitious.

2.4. Phase 4: Interpretation. A final place for analyzing and interpreting results is needed, where goal and scope definition sets the focus, and inventory analysis and impact assessment comprise data collection and calculations. This place is provided by the fourth phase of the LCA framework, the interpretation. It basically is concerned with three different types of activities:

1. An evaluation of the results obtained so far.
2. An analysis of these results.
3. Drawing conclusions and making recommendations.

These three activities are discussed below.

It will be clear that the results of an LCA are not completely certain. Large amounts of data are needed, and some of these data may be of poor quality. Moreover, cut-offs have been made and other simplifications and assumptions may have been introduced to make the analysis feasible. For some data items, there may be a range of values available, because different databases contradict each other. Methodological choices can be debated; the principles used for allocating multifunctional processes is just one example. Finally, normative choices, eg, as to the use of weighting factors, can be present at a number of places. All in all, an analysis of the quality of the analysis and the robustness of the results is an essential part of sound decision making. For this reason, the interpretation phase is a place par excellence to address uncertainty. A number of steps are possible for the interpretation phase (13):

1. Consistency check.
2. Completeness check.
3. Contribution analysis.
4. Perturbation analysis.
5. Sensitivity and uncertainty analysis.

Interpretation is a relatively new phase of LCA and has not yet received as much attention as the other LCA phases. Preliminary proposals for operating the interpretation steps have been elaborated (4,13). New approaches continue to be published, and the usefulness of the different approaches is being investigated.

These approaches are aided by new developments in software. A few examples of these approaches are given below.

In a contribution analysis, the results of LCA are divided into contributing unit processes and/or environmental flows. Table 8 shows the results of a contribution analysis for the emission of cadmium to freshwater yielding a decomposition into the main contributing processes for the hypothetical system of PE throw-away bags.

A perturbation analysis is a systematic method to study the influence of changes of data items. Such changes may be introduced due to statistical variation, or deliberately, by product or process improvement. An example of the result of a perturbation analysis is seen in Table 9. This table can be read as follows: If the coefficient for the output of ethylene of the process production of ethylene is increased by 1%, the system-wide emission of benzene to freshwater is decreased by 1.15%. Note that only a small number of coefficients exhibit such large sensitivities.

Sensitivity and uncertainty analysis address inherent uncertainties in data and different scenarios, assumptions, and choices. Typical forms may address

- Parameter variation, (ie, the recalculation of results with modified data and/or choices).
- Monte Carlo analyses (eg, leading to results with error bars).
- Ranking of alternatives on the basis of the number of runs for which a certain alternative ranks best or worst.

Sensitivity and uncertainty analysis are becoming accessible by the development of LCA software that supports the required calculations, the availability of databases containing uncertainty information, and methods to support the interpretation of advanced statistical methods.

The approaches mentioned often serve a double purpose: evaluation and analysis of these results. For example, a perturbation analysis will provide an indication of the robustness of the results, but also shows where improvements may be introduced. Another example is the contribution analysis: This analyses can serve the purpose of evaluation by pointing out unexpected, and therefore suspicious results, and it helps to locate key issues for improvement of products.

A final activity in the interpretation is the drawing of conclusions and the making of recommendations. Although no formal methods can be specified here, the main concern in the LCA framework is to safeguard the consistency with the goal and scope of the study, the procedural embedding, and the justification of the conclusions and recommendations.

3. Software and Data

Life cycle assessment requires the processing of data in a way that is specified by the methodological guidelines discussed above. Two elements are thus needed.

1. Data to insert into the formulas.
2. Software to perform the calculations and to visualize the results. These two elements are briefly addressed in this section.

Data appears as a requirement during the LCA process. The inventory analysis has the largest data requirements: for all unit processes considered in the product system, data on use and production of materials, products, energy and waste, as well as the use of natural resources and the release of pollutants should be quantified. Typical LCAs nowadays may address several hundreds of unit processes, each of these are linked with dozens of flows. Important sources of these data include the following:

1. Company-specific data sheets and measurements.
2. Consumer survey and questionnaires.
3. Annual reports and emission inventories and permits of companies.
4. LCA-specific general purpose databases.
5. LCA-specific specialized databases (eg, for a specific industrial sector).
6. Non-LCA general databases (eg, economic input–output tables).
7. Estimates on the basis of chemical composition, intuition, etc.

Table 10 provides references to some (not exhaustive) often-used LCA databases.

The impact assessment requires characterization factors, normalization data, and sometimes weighting factors. Characterization factors have been reported in many guidebooks for LCA, and normalization data is sometimes available in the same sources (see Table 10). Weighting factors are a dark area: Their use is discouraged by ISO for comparative assertions disclosed to the public, and there is some divergence as to principles.

Calculations in LCA are in principle straightforward and can thus be done by hand or in a simple spreadsheet. However, the large databases available today and the development of advanced analyses (eg, statistical analyses) make the use of dedicated software programs indispensable. There is quite a diversity of choice here.

1. Some focus exclusively on LCA specialists.
2. Some contain databases with data for inventory analysis and/or impact assessment.
3. Some have a large methodological freedom (eg, in choosing alternative allocation principles).
4. Some have advanced modes of analysis (eg, supporting Monte Carlo simulations).
5. Some focus on specific industrial sectors or specific applications (like design).
6. Some concentrate on (or are restricted to) inventory analysis.
7. Some provide graphic handling of unit processes.

8. Some support sharing of data.
9. Some are cheap or for free.
10. Some are open source.
11. Some are user-friendly.

Software overviews and reviews have been published by several authors (30–34).

4. Procedural Embedding

The theoretical framework and methodology of LCA is one thing, conducting an LCA study in practice is another. There are many ways to conduct an LCA study, and they depend on the intended application. If the study solely serves internal purposes (eg, learning LCA methodology in itself or exploring possible problematic areas of a particular product), the LCA study is merely an analytical activity. In such an application, there are no stakeholders involved and conducting an LCA may be quite a straightforward activity. However, if the study is commissioned (eg, by the internal management or by an external organization), not only is the practitioner involved in the study, but there is also a commissioner. Then, it might be wise to organize a platform for dialogue between the practitioner and the commissioner to clearly set the goal and scope of the study and to discuss choices and assumptions to be made with mutual agreement between them. Moreover, the results may steer decision-making involving various stakeholders with diverging views. In such cases, problems often rise on the authoritativeness of the results of the LCA study: Stakeholders may not always accept the outcomes of the study. LCA has, eg, been used for public applications such as for governmental policy (examples concern the use of LCA as a decision-support tool in national packaging policies and for drafting long-term waste management plans). LCA has proven to be valuable, but, especially in packaging policy applications, has also caused problems with respect to the authoritativeness of results.

When LCA is applied in situations involving various stakeholders having diverging interests, it is particularly important to involve stakeholders in the study. Several authors have acknowledged this importance (35) and a few have tried to develop procedural guidelines to determine how input and interests of stakeholders can be dealt with in the course of an LCA study. Among these few are De Bruijn and Van Duin who developed procedural guidelines for six different decision situations (13).

Although development and application of such procedural guidelines is relatively new and not yet widespread, it is already common practice to have LCA studies peer reviewed. This is especially the case of LCA studies used for external purposes and involving different stakeholders, but it is also becoming more and more common for internal studies. The ISO 14040 has set the standard for this study and describes different options for critical reviews: (1) internal expert review; (2) external expert review; and (3) review by interested parties. When LCA results are used in a comparative sense (comparative assertions), a critical review is mandatory (“since this application is likely to affect interested parties that are external to the LCA study"), according to § 7.2 of ISO 14040. In the event of a "comparative assertion that is disclosed to the public" ISO 14040, clause 5.1 (1) requires a "review by interested parties". Moreover, ISO 14040 imposes quality requirements on the reporting of results, data, methods, assumptions, and limitations.

5. LCA In Practice

Life cycle assessment originated in the early 1970s. In this initial period, studies were performed in a number of countries, in particular Sweden, the United Kingdom, Switzerland, and the United States. The products that received primary attention were beverage containers, a topic that has dominated LCA discussions for a long time. During the 1970s and the 1980s, numerous studies were performed, using different methods without a common theoretical framework. Under the coordination of the Society of Environmental Toxicology and Chemistry (SETAC), ISO, and the SETAC-UNEP Life cycle Initiative, this situation has significantly improved and is continuing to improve. Whereas in the 1990s the focus was on development and standardization of methodology, the current trend of research activity is much more application driven.

Today, LCA is applied at different levels. On the one hand, LCA can be used at an operational level for product improvement, product design, and development, as well as for product comparison. The latter is, eg, at stake in the underpinning of ecolabeling programs (36), purchase preference schemes, and other environmental communications. On the other hand, LCA can be used at a strategic level, either by companies or authorities. Within firms, LCA may give guidance for business strategies, including decisions on which type of products to develop, which type of resources to purchase, and which type of investments to make for waste management. For authorities, an application of increasing importance is the comparison among contrasting environmental policy options (eg, in the field of waste management, of energy policy, or of transportation). A recent example concerns the proposal of "overall business impact assessment" (OBIA), being an LCA for a company as a whole (37). Finally, LCAs are often experienced as educationally beneficiary (eg, a company learning about its activities in relation to the environmental problem and how they can help correct these problems themselves) (38).

LCA has been applied to a wide range of products and services (39–41). Hundreds of LCA case studies are known and can be found in the literature or on the web. Even more studies have been made for company-internal purposes, without publication in the scientific literature or on the web. Life cycle assessment has been applied to such simple products as shopping bags and packaging to complex products such as cars and PCs. Studies may involve both an environmental comparison between existing products and the development of new products (eco-design). LCA can also be applied to processes, services, and activities. Examples of nonproduct LCA studies are LCAs on hazardous waste site clean-up options, on waste management strategies, and on different modes of freight transport (road, rail, water). In the case of product LCAs, it is the function provided that is the core object of the LCA project, but in this case the function is cleaning up a hazardous waste site, waste management, or freight transport.

An emerging concept is life cycle management (LCM), which is an integrated approach for managing the total life cycle of goods and services toward more sustainable production and consumption. LCM uses various procedural and analytical tools taken from the Product Sustainability Toolbox for different applications and integrates economic, social, and environmental aspects into an institutional context. Life cycle management is applicable for industrial and other organizations demanding a system-oriented platform for implementation of a preventive and sustainable driven management approach for product systems (34).

There are different system analysis tools available for what might be called a toolbox for Green Chemistry or Industrial Ecology [eg, Risk Assessment (RA)], Substance Flow Analysis (SFA) of Material Flow Analysis (MFA), Environmental Impact Assessment (EIA), Technology Assessment (TA), Cost-Benefit Analysis (CBA), etc. Besides the fact that all of these tools are still being developed, it is of the utmost importance that the application field of these tools be clearly distinguished so that the right tools are used for answering the given questions. It has become increasingly clear that LCA is just one tool for environmental analysis amidst others for dealing with a given situation (42). The starting point for an LCA study is a decision situation in which a choice between a number of alternative product or technology systems is to be made. Other tools may be more relevant than LCA in some circumstances, (eg, RA if local aspects of one of the technologies is central in the decision to be supported or SFA if one specific flow substance is of prime importance in the product system investigated). Often no one single tool is the most appropriate for a specific question, but different tools may be used in combination to provide additional insights into the various environmental consequences of a choice. Different tools applied for the same decision may even produce conflicting insights and the results of these tools are thus complementary. Although this fact may complicate the decision at stake, it is not possible to create one super-tool integrating the added values of all of these individual tools.

6. The Future of LCA

Life cycle assessment is an active research area in terms of methodology, as well as practical aspects. Methodology developers are working hard on further improving different parts of the LCA method (eg, allocation and impact assessment methodologies). Even more important is the ongoing work on incorporating uncertainty analyses in LCA. Until recently, this issue was underexposed by both methodology developers and practitioners. As it is very difficult to have an encompassing quantification of uncertainties, since much data are used in LCA for which standard deviation data are missing, it is even more complex to quantify the influence of different methodological choices and different assumptions. Work on this is progressing as shown above in the section on Interpretation, but more efforts are needed in this area in order to further mature the LCA science.

Closely related to the uncertainty issue is the issue of data availability and data quality. On the one hand, an increasing number of databases have become available (see Table 10). A number of these databases are, however, linked to specific software packages, often not format compatible and thus not easily exchangeable. They have limited geographical validity while they may heavily overlap in background data, but for the user this is not traceable. In the past, most of the databases didnot include specific fields for quality assessment of data entries, but this is now clearly improving. However, the real uncertainties attached to the different process data are still unknown and are approached by default values (eg, standard deviations). There is thus still a need for harmonization of data and for combining national databases into a highly qualified central database with related management.

For LCA in practice, not only improvement of databases, but also further improvement of software, is important. There are two apparently contradicting developments: (1) advanced software; (2) simplification. On the one hand, LCA software is getting evermore advanced and includes Monte Carlo analyses, allocation scenarios, and other sophisticated features. On the other hand, simplification of LCA tools and more customized tools are foreseen (eg, for application within small- and medium-sized enterprises (SMEs) who have difficulty in transposing their daily practice to the theoretical world of LCA).

Last, but not least, the UNEP/SETAC life cycle initiative should be mentioned here (see http://www.uneptie.org/pc/sustain/lcinitiative/background.htm). In short, the aim of this initiative is to put life cycle thinking into practice and to improve the supporting tools through better data and indicators. The potential for international harmonization of methods and data that may be achieved through this initiative is both huge and challenging. Part of the Initiative is the program on LCM (see http://www.uneptie.org/pc/sustain/lcinitiative/lcm_information.htm). As this initiative is still evolving on a daily basis, we refer here to the websites mentioned above for more and up-to-date information.

All of these developments clearly show that LCA science cannot be an "ivory tower" issue. LCA scientists must focus on developing better and more sophisticated methods, but they should not lose contact with the eventual users. As LCA is not only science, but also serves a societal aim (getting a more sustainable environment) a proper balance has to be found (43).

7. Selected Web Site Addresses Relating to LCI and LCIA Data

APME	http://www.apme.org/
Buwal 250	http://www.umwelt-schweiz.ch/buwal/eng/fachgebiete/fg_produkte/umsetzung/oekobilanzen
Boustead model	http://www.boustead-consulting.co.uk/products.htm
Eco-indicator 99	http://www.pre.nl/eco-indicator99/ei99-reports.htm
Ecoinvent2000	www.ecoinvent.ch
FEFCO	http://www.fefco.org/index.php?id=62
IVAM LCA DATA 4	http://www.ivam.uva.nl/nl/
Japanese Database	http://www.jemai.or.jp/lcaforum/index.cfm
CML-impact assessment factors	http://www.leidenuniv.nl/cml/ssp/databases/cmlia/index.html

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Jeroen B. Guinée
Renout Heijungs
Institute of Environmental Sciences (CML),
Leiden University

Table 1. **Some Key Guidebooks on LCA**

Commissioner/publisher	Publication date	Reference
Society of Environmental Toxicology and Chemistry (SETAC)	1991	5
Nordic Council of Ministers	1992	6
Dutch government	1992	7
SETAC	1993	8
US-Environmental Protection Agency (US-EPA)	1993	9
Nordic Council of Ministers	1995	10
McGraw-Hill	1996	11
Danish government	1998	12
Dutch government	2002	13
Asia–Pacific Economic Cooperation (APEC)	2004	14
Chalmers University of Technology	2004	15

Table 2. **Inventory Results for the Hypothetical System of PE Throw-Away Bags**

Intervention	Value	Unit
Resources		
crude oil	8.1	kg
Emissions to air		
1-butene	7.8×10^{-7}	kg
benzene	9.9×10^{-7}	kg
carbon dioxide	2.2	kg
dioxins (unspecified)	8.1×10^{-14}	kg
ethylene	1.2×10^{-4}	kg
nitrogen oxides	3.7×10^{-3}	kg
sulfur dioxide	2.0×10^{-2}	kg
Emissions to water		
benzene	1.2×10^{-9}	kg
cadmium	4.4×10^{-8}	kg
lead	3.0×10^{-9}	kg
mercury	2.8×10^{-9}	kg
phenol	2.4×10^{-8}	kg
Economic inflows not followed to the system boundary		
lubricants	2.4	kg
Economic outflows not followed to the system boundary		
used plastic bag	1×10^{3}	
residue to dump	8×10^{-2}	kg
recovered energy	80	MJ

Table 3. **Illustration of the Concepts Involved in Characterization**

Item	Example
impact category	climate change
LCI results	emissions of greenhouse gases to air (in kg)
characterization model	the model as developed by the Intergovernmental Panel on Climate Change (IPCC) defining the global warming potential of different greenhouse gases
category indicator	infrared radiative forcing (W/m^2)
characterization factor	global warming potential for time horizon of 100 years (GWP_{100}) for each greenhouse gas emission to air (in kg carbon dioxide/kg emission)
unit of indicator result	kg (carbon dioxide equiv)

Table 4. **Examples of Characterization Models and Factors for a Number of Important Impact Categories**

Impact category	Characterization model	Characterization factor[a]
abiotic depletion	-	ADP
climate change	IPCC model	GWP
stratospheric ozone depletion	WMO model	ODP
human toxicity	Multimedia model, eg, EUSES, CalTox	HTP
ecotoxicity (aquatic, terrestrial etc)	Multimedia model, eg, EUSES, CalTox	AETP, TETP, etc
photooxidant formation	UNECE Trajectory model	POCP
acidification	RAINS	AP

[a] ADP = abiotic depletion potential. ODP = ozone depletion potential. AETP = aquatic ecotoxicity potential. AP = acidification potential. GWP = global warming potential. HTP = human toxicity potential. TETP = terrestrial ecotoxicity potential. POCP = photochemical ozone creation potential.

Table 5. **Environmental Profile for the Hypothetical System of PE Throw-Away Bags**

Impact category	Value	Unit
depletion of abiotic resources	3.5	kg antimony equiv
photooxidant formation	1.2×10^{-4}	kg ethene equiv
climate change	2.2	kg CO_2 equiv
freshwater aquatic ecotoxicity	0.013	kg 1,4-DCB equiv
terrestrical ecotoxicity	2.6×10^{-6}	kg 1,4-DCB equiv
human toxicity	0.0088	kg 1,4-DCB equiv
acidification	0.033	kg SO_2 equiv
eutrophication	4.8×10^{-4}	kg PO_4 equiv

Table 6. **Normalized Environmental Profile for the Hypothetical System of PE Throw-Away Bags**

Impact category	Value	Unit
depletion of abiotic resources	2.2×10^{-11}	year
photooxidant formation	2.6×10^{-15}	year
climate change	5.7×10^{-14}	year
freshwater aquatic ecotoxicity	6.7×10^{-15}	year
terrestrical ecotoxicity	6.8×10^{-18}	year
human toxicity	1.8×10^{-16}	year
acidification	1.1×10^{-13}	year
eutrophication	3.7×10^{-15}	year

Table 7. **Weighting Results for the Hypothetical System of PE Throw Away Bags Using a Hypothetical Set of Weighting Factors**[a]

Impact category	Weight	Value	Unit
Weighted indicator results			
depletion of abiotic resources	0.01	2.2×10^{-13}	year
photooxidant formation	0.8	2.1×10^{-15}	year
climate change	2.4	1.4×10^{-13}	year
freshwater aquatic ecotoxicity	0.2	1.3×10^{-15}	year
terrestrical ecotoxicity	0.4	3.9×10^{-18}	year
human toxicity	1.1	1.9×10^{-16}	year
acidification	1.3	1.4×10^{-13}	year
eutrophication	1.0	3.7×10^{-15}	year
total		5.1×10^{-13}	year

[a]These weighting factors are used here for purely illustrative purposes and should not be used in any real-world application.

Table 8. **Contribution Analysis**

Process	Contribution (%)
electricity production	56
refining; allocated to naphtha	25
incineration of chemical waste	19

Table 9. **Result of a Perturbation Analysis for the Emission of Benzene to Freshwater**

Process	Flow	Multiplier
production of ethylene	output of ethylene	−1.15
production of PE	input of ethylene	0.92
production of PE	output of PE	0.92
production of plastic bags	input of PE	0.92
production of plastic bags	output of plastic bags	0.92
packaging a loaf	output of loaves packaged	0.92
refining	output of naphtha	0.90
production of ethylene	input of naphtha	0.90
packaging a loaf	input of plastic bags	0.70
rest (19 items)		<0.1

Table 10. **References to Some Often-Used LCA Databases**

Name	Domain	Website
Ecoinvent2000	energy, transport	www.ecoinvent.ch
Buwal 250	packaging materials	http://www.umwelt-schweiz.ch/buwal/eng/fachgebiete/fg_produkte/umsetzung/oekobilanzen/index.html
APME	plastics	http://www.apme.org/
Boustead model	fuels and materials	http://www.boustead-consulting.co.uk/products.htm
Japanese Database	all kinds of materials and fuels	http://www.japanfs.org/db/database.cgi?cmd=dp&num=411&UserNum=&Pass=&AdminPass=&dp=data_e.html
FEFCO	corrugated board	http://www.fefco.org/index.php?id=62
IVAM LCA DATA 4	building materials, plastics, metals, agriculture, electro-technical industry, waste management	http://www.ivam.uva.nl/nl/
Eco-indicator 99	all kinds of materials, fuels and waste processes	http://www.pre.nl/eco-indicator99/ei99-reports.htm

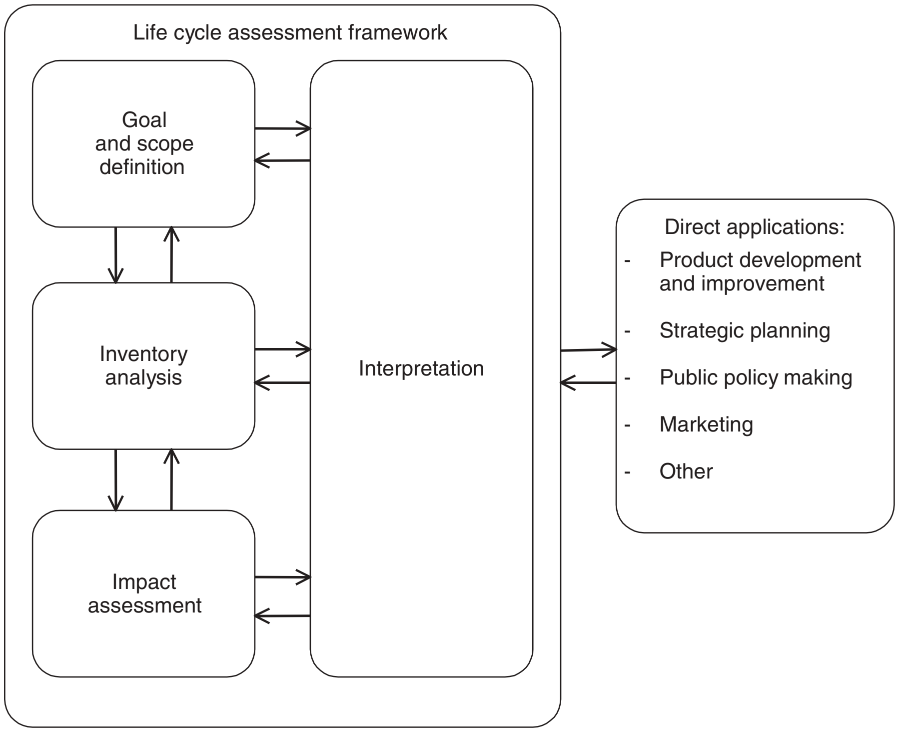

Fig. 1. Methodological framework of LCA: phases of an LCA (1).

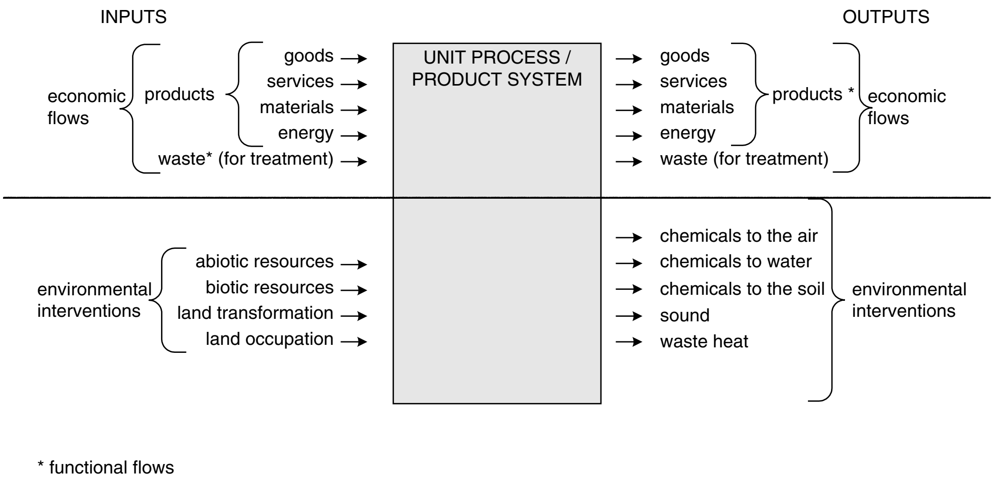

Fig. 2. Data categories distinguished by Guinée and co-workers (13).

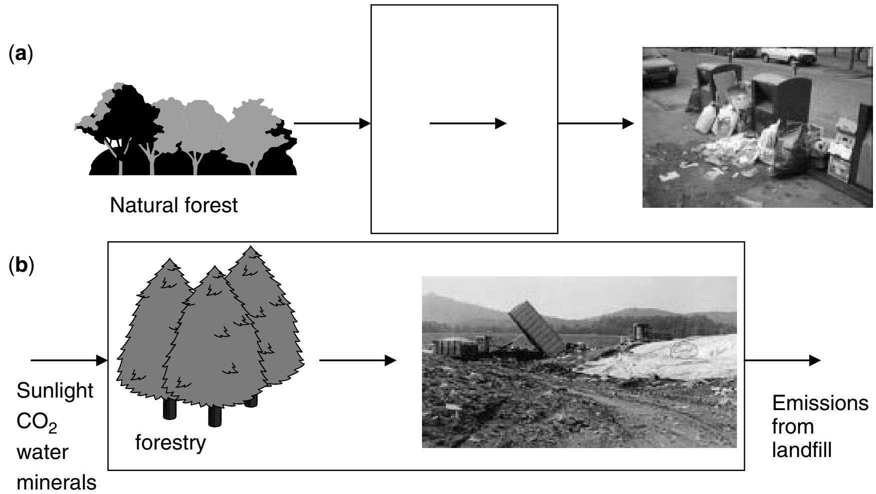

Fig. 3. Two ways of defining system boundaries between the physical economy and the environment in LCA: (**a**) with narrow system boundaries, (**b**) with extended boundaries. The general recommendation is to adopt option **b**.

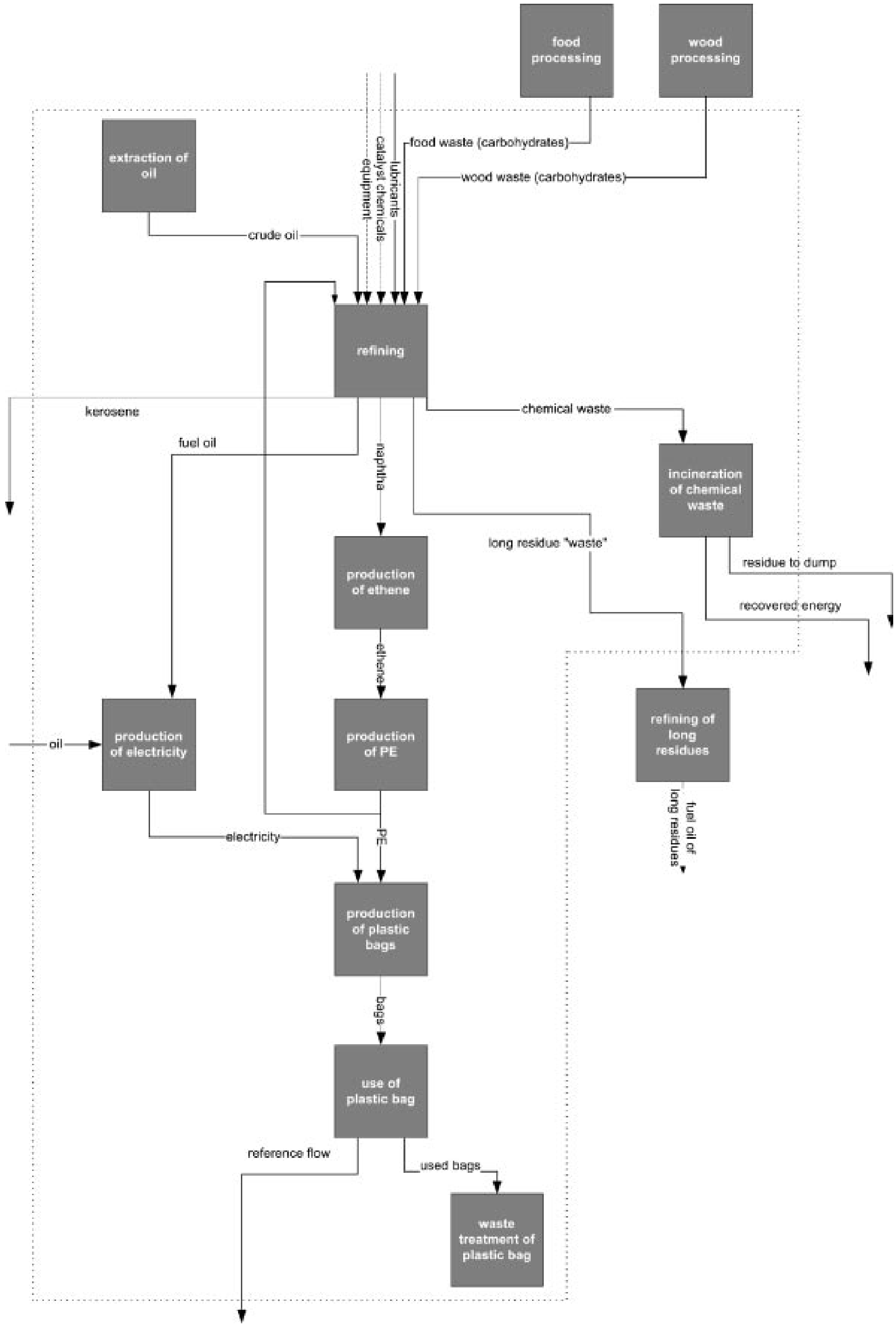

Fig. 4. Simplified flow diagram for the hypothetical system of PE throw-away bags used to package bread. The reference flow is about the bundle of packaging functions such as conserving and protecting.

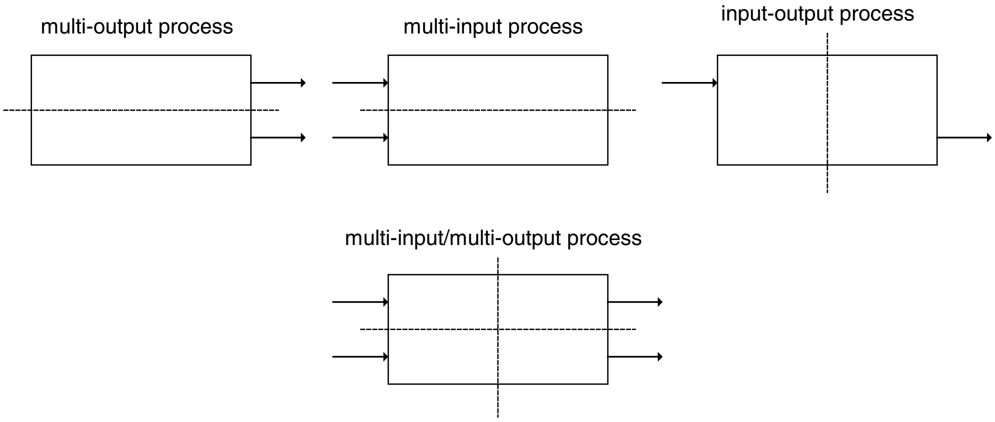

Fig. 5. Basic types of multifunctional processes, and their combination. Functional flows to which all other flows are to be allocated are shown as arrows. Other flows have been omitted from the figure. System boundaries are depicted as dotted lines.