Executive Summary

Life cycle assessment (LCA) has been developed as a tool for assessment of the environmental impacts which are caused by the pressures from products or systems, viewed in a life cycle perspective, i.e. covering all stages of the life cycle of the product or system from the extraction of raw materials over manufacture or construction through use to disposal or decommissioning and recycling. It is a holistic tool in the sense that it models all relevant environmental impacts from the global (like climate change and ozone depletion) to the local (like land use) and also the loss of resources. The framework for LCA has been standardised by the International Standards Organisation, ISO, which identifies four phases – Goal and scope definition, where the goal is defined, the service to be provided by the studied system is quantified in terms of the functional unit of the study, and the product system is defined, Inventory analysis where data for the physical flows to and from all processes in the life cycle is collected and related to the functional unit, Impact assessment, where the physical flows are translated into impacts on the environment and resource base, and Interpretation where the outcomes of the earlier phases are interpreted in relation to the goal of the LCA. LCA is typically used for comparisons, and in order to facilitate the comparison of the rather diverse environmental impacts which are comprised by the Life Cycle Impact Assessment (LCIA) methodology, procedures have been developed for normalisation and valuation which support aggregation and comparison across the different impacts. The resulting impact scores are seen as representing potential impacts rather than real effects due to:
- The lack of knowledge about geographical conditions of most of the processes in the product system and the background conditions of the receiving environment
- The aggregation of emissions over time and space
- The fact that the emissions in the inventory represent the impacts from a functional unit, which for products often constitutes a minute fraction of the total output from the manufacturing stage. For waste management systems, it is pointed out, that these aspects may be less of a problem than for the typical product systems for which LCA was originally developed, since the environmental impacts from waste management systems are typically dominated by one or a few central waste treatment processes for which both the location, receiving environments and temporal emission profiles can be well known. The emissions of persistent pollutants from landfills does, however, pose special problems to LCIA due to an emission pattern characterised by a very long duration and very low concentrations of the emissions, which is quite different from the typical emission patterns
from other processes in the life cycle, and which really requires a more risk-oriented assessment procedure than what is normally applied in LCIA.

Finally, some of the topical discussions within the LCIA method development community are introduced, including questions like
- How large a part of the environmental mechanism should we model?
- For waste management systems (particularly for landfills), it is relevant to include site-specific information in the assessment - is it also possible?
- (When) can we develop global recommendations for the life cycle impact assessment?

INTRODUCTION

Life cycle impact assessment is that phase of life cycle assessment (LCA) where the inventory of material flows in the life cycle of a product or a system are translated into environmental impacts and consumption of resources. The environmental impacts range from very local (e.g. land use) to global (like climate change). LCA is focused on the product system or system of processes, which are needed to fulfil the function provided by the product or system – from the extraction of raw materials via manufacture or construction to use and maintenance and finally disposal or decommissioning and recycling, or in short from the cradle to the grave (see Figure 1). This sets the frame for life cycle impact assessment (LCIA), and has consequences for current LCIA methodology which are discussed below.

![Figure 1. The product life-cycle or product system proceeds from raw material extraction over manufacture of materials, components and semi-products to assembly of the product and via distribution to use, disposal and possibly recycling of components or materials. Processes and life-cycle stages may be linked by transportation processes (circumscribed T), and throughout the product system, waste is generated (circumscribed W).](image)

Life cycle assessment has found a widespread use in industry’s development and marketing of products. It is a cornerstone of the integrated product policy (IPP), which is under development in the EU aiming to reduce environmental impacts from consumption of products (Oosterhuis et al., 1996, CEC, 2001), and it is prescribed by EU as analysis tool in the development of waste management systems (EU, 2005).

A framework for LCA has been standardised by the International Organisation for Standardisation (ISO) (ISO, 1997). It consists of the following elements:

*Goal and scope definition* defines the goal and intended use of the LCA and scopes the assessment in terms of setting the boundaries of the product system (Figure 1), and defining the temporal and technological scope, and assessment parameters of the LCA. The function to be provided by the
system is quantified in the functional unit which defines the reference flow of products for a product LCA. For a packaging study, the functional unit may thus be “packaging of 1000 litres of milk in 1 litre containers” identifying that the relevant comparison may be between 1000 carton boxes and 40 returnable PC-bottles (which on average can be used 25 times). For a system LCA the functional unit will give a quantitative definition of the function to be obtained by the system e.g. treatment of 100.000 tons municipal solid waste per year for ten years in compliance with existing regulations.

Inventory analysis collects data on input and output for all processes in the product system and relates them to the reference flow given in the functional unit. The data is typically presented in an aggregated form as total emissions of substance X or total use of resource Y for the product system.

Life cycle impact assessment is the phase of the life cycle assessment where inventory data on emission loads and resource use are translated into information about the product system’s impacts on the environment, on human health and on resources.

Interpretation is the phase of the LCA where the results of the other phases are interpreted according to the goal of the study using sensitivity and uncertainty analysis.

RESTRICTIONS ON LIFE CYCLE IMPACT ASSESSMENT

The focus on a product system has some important implications which set the boundary conditions when impacts are assessed for the results of the life cycle inventory.

The emissions from the product system are normally separated from each other both in time and in space. With the globalisation of our economy, processes can take place in most parts of the world and for most products, the product system is globally extended. The life cycle of the product may last several years from the extraction of resources to the final disposal of the product, and if parts of it are landfilled, emissions may continue to occur for centuries or even longer. The spatial and temporal conditions are vaguely resolved for many processes, and typically emissions are aggregated over the life cycle. In practice, a very different emission scenario where the full quantity is discharged from one process in a pulse emission would thus lead to the same life cycle inventory result. The impact assessment has to operate within the restriction that the emissions are aggregated over time and space, and for many processes, knowledge about the geographical location is very limited.

The inventory analysis collects data on the in and output associated with the functional unit. Typically, the object of the study represents a small fraction of the daily output from the production processes, and the emissions to air, water or soil, which are listed in the inventory, represent the equivalent fraction of the total emissions from the process. They are typically determined from a mass balance over the process, are presented as mass loads (kg per functional unit), and are normally unaccompanied by information about the temporal course of the emission or the resulting concentrations in the receiving environment. Life cycle impact assessment thus has to operate on mass loads representing a share (often infinitesimal) of the full emission output from the processes.

CHARACTERISTICS OF LIFE CYCLE IMPACT ASSESSMENT

The impact assessment phase interprets the inventory results in terms of their potential impacts on what is referred to as the “areas of protection” of the LCIA, i.e. the entities that we want to protect by using the LCA. Today, there is acceptance in the LCA community that the protection areas of
Areas of protection for LCIA

- Human health
- Natural environment
- Natural resources
- Man-made environment

Impacts on the areas of protection are modelled applying current knowledge about relations between emissions and their effects in the environment as illustrated in Figure 2.

Figure 2. Schematic presentation of an environmental mechanism underlying the modelling of impacts and damages in life cycle impact assessment.

For greenhouse gases like CO$_2$ and CH$_4$, an impact early in the environmental mechanism would be an increment in the atmosphere’s ability to absorb infrared radiation. Among later impacts in the mechanism are an increase in the atmospheric heat content, propagating to the global marine and soil compartments causing changes in regional and global climates and sea-level rise, eventually damaging several of the areas of protection: human health, natural environment and man-made resources. The fate processes in Figure 2 would be the degradation and transport of the gas in the troposphere, the stratosphere, and the global water and soil compartments, and they would be interwoven in the chain of impacts all the way from emission to the areas of protection.

For the consumption of resources, severity is typically derived from the scarcity of the resource.

A holistic perspective on environmental impacts
Life cycle impact assessment applies a holistic perspective on environmental impacts and in principle attempts to model any impact from the product system which can be expected to damage one or more areas of protection. This means that LCIA addresses not only the toxic impacts (as environmental risk assessment does) but also the other impacts associated with emissions of air
pollutants (global warming, stratospheric ozone depletion, acidification, photochemical ozone and smog formation) or waterborne pollutants (eutrophication and oxygen depletion), as well as the environmental impacts from different forms of land use, from noise and from radiation, and the use and loss of renewable and non-renewable resources. Some LCIA methods even include the human health impacts from the occupational exposure from operating the processes in the life cycle (Wenzel et al., 1997).

At present, it is normal to restrict LCIA to environmental impacts and not to address social impacts or cost aspects in the life cycle. The latter are covered by a separate discipline, life cycle costing, developed independently from the LCA methodology and not covered by the ISO standards on LCA. The omission of social impacts from LCIA is to some degree inconsistent with the defined areas of protection since social impacts will often lead to impacts on human health, and indirectly on the sustainable use of ecosystems. Attempts are on-going to develop LCIA for social impacts (United Nations Environment Programme, 2002, Dreyer et al., 2006).

The steps of LCIA

The ISO standard defines four steps for life cycle impact assessment:

First step is Selection of impact categories and classification. Here, categories of environmental impacts of relevance to the study are defined. In most LCA studies, existing impact categories can just be adopted. Next, the substance emissions from the inventory are assigned to the impact categories according to their ability to contribute to different environmental problems. Figure 3 shows environmental impact categories which are often modelled in LCIA.

Second step is Characterisation where the impact from each emission is modelled according to the environmental mechanism (Figure 2) and expressed as an impact score in a unit common to all contributions within the impact category (e.g. kg CO₂-equivalents for all greenhouse gases). Following characterisation, the contributions from different substance emissions can be summed within each impact category, and the inventory data translated into a profile of environmental impact scores and resource consumptions.

Third step is Normalisation where the different impact scores and resource consumptions are related to a common reference in order to facilitate comparisons across impact categories. Life cycle assessment is often used for comparative studies (“is alternative “A” preferable to alternative “B”?”), and comparison across impact categories is necessary when there are trade-offs between the categories, i.e. when improvements in one impact score are obtained at the expense of another impact score. Normalisation expresses the relative magnitude of the impact scores on a scale which is common to all the categories of impact (typically the background impact from society’s total activities).

Fourth and final step of the impact assessment is Valuation where a ranking or weighting is performed of the different environmental impact categories and resource consumptions reflecting the relative importance they are assigned in the study. The valuation is needed when trade-off situations occur as described under normalisation. Where normalisation expresses the relative magnitudes of the impact scores and resource consumptions, valuation expresses their relative significance considering the goal of the study.

According to the ISO standard, the first two steps of the impact assessment are mandatory while normalisation and valuation are optional (ISO, 1997). The valuation step is the most normative part of the methodology. Here, preferences and stakeholder values are applied, and there is no objective way to perform the valuation, and hence no “correct” set of ranks or weighting factors. The ISO
standard for LCIA does not permit valuation in studies supporting comparative assertions disclosed to the public (ISO, 2000).

The ISO standard for LCIA refrains from a standardisation of detailed methodological choices. Over the last decade, several well-documented methodologies for life cycle assessment have been developed filling this gap (Wenzel et al., 1997; Heijungs et al., 1992; Hauschild and Wenzel, 1998; Goedkoop and Spriensma, 2000; Steen, 1999; Guinée, 2002; Bare et al., 2003; Itsubo and Inaba, 2003). Figure 3 shows an output from one of these methodologies.

![Figure 3. Impact profiles for two refrigerator designs showing the impact scores for a number of environmental impact categories. All impacts have been normalised and are expressed in a common unit – the person equivalent, PE (or rather milli PE), representing the annual impact from an average person. Decisions based on a comparison between impact categories require some sort of valuation as not all impact categories can be assumed to have the same importance. The profiles have been made applying the EDIP97 LCIA methodology (Wenzel et al., 1997).](image)

**Comparison across impact categories calls for best estimate in modelling**

LCIA covers a multitude of environmental impacts and supports comparison between them. Characterisation modelling must therefore aim for the same degree of realism for every category of impact to avoid a bias in the comparison between the categories. LCIA aims for best estimates in the modelling of all impacts. For most impact categories, this means that existing environmental models can be adopted for the characterisation. For climate change, the global warming potentials of the Intergovernmental Panel of Climate Change (IPCC) are thus the most frequent choice as characterisation factors. For the categories representing toxic impacts on humans and ecosystems, however, the need of best estimate impact modelling entails a different approach from what is commonly applied in generic environmental risk assessment. Here, a conservative approach will often be used, applying realistic worst case estimates in order to be on the safe side in identifying situations posing potential risks of toxic effects (Hauschild and Pennington, 2002).

The quest for best estimates in characterisation modelling potentially brings LCIA into conflict with one of the fundamental principles of sustainable development (see also Tukker, 2002). In the Rio declaration, the precautionary principle states that where there are threats of serious or irreversible
damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation (United Nations, 1992). In case of insufficient knowledge, the precautionary principle thus sanctions a conservative approach if the damage can be irreversible or serious in other ways. The conflict with the precautionary principle can partially be overcome in the valuation step by assigning higher weights to those impact categories where precautionary considerations justify it.

**Impact scores represent potential impacts, not real effects**
The emission inventory consists of fractions of the total emissions from processes of the product system, aggregated over time and space. The calculated impacts hence represent a sum of impacts from emissions which were released years ago and from emissions which will be released some time in the future. Furthermore, the impacts affect different ecosystems in different parts of the world depending on where the processes are located. In the real world, environmental effects arise at a specific point in time and space as a consequence of the total impact affecting the ecosystem. In LCA we have no knowledge about the simultaneous emissions from other processes, outside the product system, which expose the same ecosystem, and also no information about the background concentration of other substances in the ecosystem. It is thus difficult to interpret the impacts which are modelled in LCIA in terms of real effects on the environment. They are rather seen as environmental performance indicators which can be the basis of comparisons and optimisation of the system or product, but they tell us little about the resulting effects on the environment. Product systems are fictitious entities that we cannot monitor in the real world, and characterisation models applied in LCIA are therefore difficult to validate. Their validity is typically based on their being derived from commonly accepted environmental models which are adopted to operate within the restrictions posed by LCA.

For LCA of waste management systems, the functional unit may be the full operation of the system to treat the annual production of waste in a region, and some processes may be so dominant and geographically well-defined that it may actually be possible and meaningful to interpret the impacts into effects on the environment. In this case, the life-cycle impact assessment evolves in the direction of environmental risk assessment (ERA) or environmental impact assessment (EIA) where spatial and temporal dimensions are much better defined in the analysis of the environmental impacts from a specific facility, for example an incinerator or composting plant.

**Temporal aspects for landfills**
The analysis of landfills poses a special challenge to LCIA because emissions result over time, as opposed to instantaneously as is the case for most industrial processes, where emission will occur over minutes, hours, or at most weeks. However, a life-cycle inventory only reports the quantities emitted per functional unit, not the rate of emission. Since an exposed ecosystem reacts to the environmental concentration and not to the total emitted quantity, the “release over time” will influence the effects that can be observed from the emissions. This issue is most difficult for metals where the concentration in leachate may persist for centuries or even millennia (Helweg, 2001). In the case of metals, the release with time is many orders of magnitude larger than what is the case for industrial processes, and for these emissions, the results of the life-cycle impact assessment may become meaningless due to the lack of temporal differentiation. The total quantity of copper emitted from an electronic product deposited in a landfill may thus be so high, that the associated ecotoxicity impact potential completely dominates the impact assessment results. The release with time, however, means that the copper-concentration in the leachate will be so low that no actual effects will be caused by this emission. As mentioned above, life-cycle impact assessment is not concerned with prediction of actual effects for various reasons. Its results should, however, be in accordance with general experience from environmental science. The discrepancy observed for landfilling of persistent substances remains an unsolved problem in life-cycle impact assessment.
CURRENT DEVELOPMENTS IN LIFE CYCLE IMPACT ASSESSMENT

Life cycle assessment is a young discipline, mainly developed from the mid-1980’s until now. Throughout the 1990’s, a number of consecutive international working groups under the Society of Environmental Toxicology and Chemistry (SETAC) took the methodology development and consensus building a good step forwards (Consoli et al., 1993, Fava et al., 1993, Udo de Haes, 1996, Udo de Haes et al., 2002), but LCIA is still a discipline in vivid development. Some of the central current discussions are reviewed below.

Midpoints and endpoints in characterisation modelling

Traditional characterisation methods model the impact on an indicator located at the point between emission and endpoint in the environmental mechanism where it is judged that further modelling is not feasible or involves too large uncertainties (a “midpoint”, see Figure 2). Representatives of the midpoint school are Wenzel et al. (1997), Heijungs et al. (1992), Guinée (2002), Bare et al. (2003), and Hauschild and Potting (2003).

An alternative school of characterisation modelling takes as starting point that the purpose of LCA is to reveal impacts on the areas of protection, and that consequently, LCIA must model impacts on these. Characterisation modelling must therefore include the entire environmental mechanism, since the areas of protection are located at the endpoint of it (see Figure 2). The most important representatives of the endpoint school are Goedkoop and Spriensma (2000), Steen (1999), and Itsubo and Inaba (2003).

Proponents of the endpoint school find that the increased uncertainty in the characterisation modelling is justified by a reduced uncertainty in the interpretation of the results. Some decision makers prefer results of the LCIA to be expressed in separate impact categories, which they can relate to, but in case a valuation is needed, it only concerns the four areas of protection in an endpoint approach, where the midpoint approaches must valuate a higher number of midpoint-based impact scores. This valuation must somehow interpret the potential to cause impacts on the areas of protection (Bare et al., 2000), e.g. through a semi-quantitative analysis of the un-modelled parts of the environmental mechanism, considering aspects like severity and reversibility of the impacts on endpoints, their geographical extent and expected duration, and the uncertainty of the models predicting them (Hauschild and Wenzel, 1998) – aspects, which the endpoint approaches try to model quantitatively. Obviously, this valuation of midpoint results introduces additional uncertainty to the midpoint approaches. Different types of uncertainty thus have to be pondered when choosing the position of the midpoint impact indicator; the statistical uncertainty of the models and parameters which are used for modelling the indicator, and the uncertainty of interpreting the resulting indicator results in terms of damage to the areas of protection.
Figure 4. Both the uncertainty of models and parameters needed for modelling the indicator, and the uncertainty of the interpretation of the indicator results in terms of impacts on the areas of protection contribute to the overall uncertainty of the impact assessment. Both must therefore be taken into account when choosing the optimal location of the midpoint indicator - near to the endpoint (a) or early in the environmental mechanism (b) (adapted from Hauschild and Potting, 2003).

The two schools are not incompatible. They agree in the quest of modelling relevant impact indicators but disagree on whether the additional modelling uncertainty in endpoint modelling is justified by the improved interpretation of the results. This trade-off will vary between the different categories of impact as illustrated in Figure 4. While reliable endpoint modelling seems within reach for some of the impact categories like acidification and photochemical ozone formation, it lies far away for climate change, where a midpoint approach still chooses the indicator rather early in the environmental mechanism (at the level of radiative forcing).

As more and better environmental models become available, the optimal indicator point will move further towards the endpoint, and as larger parts of the environmental mechanism are included in the characterisation modelling, the midpoint approach will move towards the endpoint approach. Until they converge, the two approaches will compliment each other (Bare et al., 2000).

**Spatial differentiation – getting the exposure right**

The impacts caused by an emission depend on

- the quantity of substance emitted
- properties of the substance
- properties of the emitting source and the receiving environment

Traditional characterisation modelling only includes the first two aspects, inherently assuming a global set of standard conditions for the emission. This is not a problem for the truly global impact categories (climate change and stratospheric ozone depletion), but for other impacts, it can make a great difference. For regional or even local impacts, a global set of standard conditions can disregard large and unknown variations in the actual exposure of the sensitive parts of the environment. Sometimes differences in sensitivities of the receiving environment can have a
stronger influence on the resulting impact than those inherent properties of the substance on which the characterisation modelling is based (Bare et al., 2003, Potting and Hauschild, 1997).

LCA is a tool for pollution prevention, not for avoidance of environmental risks at specific sites. This has been part of the reason for neglecting local variation in exposure. On the other hand, the modelled impacts in LCIA must show accordance with the actual impacts caused by the product system, if the decisions based on the LCA shall lead to environmental improvements. Therefore, it is now acknowledged that spatial differentiation can be relevant in LCIA (Udo de Haes et al., 1999).

A more pragmatic reason for disregarding variation in exposure has been ignorance about the location of processes in the product system. It is, however, possible to differentiate the exposure modelling at least according to the country of emission, and derive site-dependent characterisation factors which depend on the country or region of emission as well as on the properties of the substance. Potting and co-workers find that the variation in acidification impact can be as high as three orders of magnitude between different countries within Europe (Potting et al., 1998), so even this modest level of spatial differentiation represents a real improvement of the characterisation models. Several groups have worked on developing site-dependent characterisation for LCIA (Krewitt et al., 1998, Huijbregts et al., 2000), and recently, methods supporting site-dependent characterisation of a range of non-global impact categories was published for processes in Europe (Hauschild and Potting, 2003) and in the US (Bare et al., 2003). More detailed site-specific approaches looking at the location of an emission source and the impacts on those water systems which actually receive the emissions, is not performed as an integral part of LCA today, but rather seen as part of a risk assessment, which may support the LCA as decision basis.

Towards a recommendable practice for LCIA

Today, several LCIA methods are available, and there is no obvious choice between them. Particularly for the toxic impacts there are large differences which make the conclusion depend on choice of LCIA method (Dreyer et al., 2003). While ISO has refrained from standardisation of the more detailed methodological choices, the United Nations Environment Program (UNEP) together with SETAC has launched the Life Cycle Initiative with an ambition to eliminate this obstacle for the dissemination of life cycle assessment (United Nations Environment Programme, 2002).

The Life Cycle Initiative was launched April 2002 to “develop and disseminate practical tools for evaluating the opportunities, risks, and trade-offs associated with products and services over their entire life cycle to achieve sustainable development”. An element under the initiative is to identify best practice for life cycle assessment within the framework laid out by the ISO standards and to make data and methodology for performing LCA available and applicable worldwide. For life cycle impact assessment it is the goal within three years to recommend specific characterisation methods and factors for each category of environmental impact, based on a global consensus process among experts, focusing on the scientific validity of the methods and their feasibility in LCIA. The recommendations will address the midpoint level but relations to the endpoint level will be clarified (United Nations Environment Programme, 2002).

CONCLUSION AND OUTLOOK

After two decades of development, life cycle impact assessment is still evolving within the constraints posed by the focus on a functional unit and a product system widely extended in time and space. The evolution has been governed by the simultaneous focus on scientific validity and environmental relevance of the modelled impacts on one side, and on the other side the feasibility in an LCA context.
Spatial differentiation has proven to be a sophistication which is needed for many of the modelled impacts to obtain accordance between the modelled and the actual impacts, and the years to come will probably see methodology developed which supports site-dependent characterisation at the level of countries or regions for all continents of the world.

Growing parts of the environmental mechanism is included in characterisation modelling as better environmental models become available, and it is foreseeable that midpoint modelling will converge with endpoint modelling for several categories of impact in the future.

One of the strengths of LCIA is its possibility to include all relevant environmental impacts of the studied system. The toxic impacts from chemical emissions are, however, poorly represented in current LCIA. There is a severe lack of consensus on assessment methodology, and characterisation factors are only available for a few hundred substances, no matter which existing methodology is chosen. As a consequence, toxic impacts are often excluded from the life cycle impact assessment. UNEP-SETAC’s Life Cycle Initiative is targeting the poor representation of toxic impacts in LCIA and aims for specific recommendations on methodology and characterisation factors in 2006 (United Nations Environment Programme, 2002). There is thus hope for a better representation of toxic impacts in LCIA in the future.

LCA and LCIA were once seen as tools for assessment of any kind of environmental issues, but it has become clear that the strengths and the limitations of LCIA are two sides of the same coin.

- The strong applicability to complex (product) systems extended in time and space limits the ability of LCIA to predict actual effects and to be validated on these predictions.
- The broad coverage of impacts requires best estimate modelling for all of them which makes it difficult to apply the precautionary principle in LCIA.

Future developments of LCIA must keep focused on the characteristic strengths of LCA and, rather than try to encompass everything, leave other types of issues to the relevant analytical tools. Environmental Risk Assessment, Environmental Impact Assessment and Life Cycle Impact Assessment are complimentary and not competing methods.

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