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LIFE-CYCLE ASSESSMENT

Introduction

Life-cycle assessment (LCA) is the assessment of environmental impact through the life-cycle of product systems. Cornerstone to the life-cycle approach is the understanding that environmental impacts are not restricted to localities or single processes, but rather are consequences of the life-cycle design of products and services. The product life-cycle covers all processes from extraction of raw material, via production, use, and final treatment or reuse (Wenzel, Hauschild et al. 1997; Guinée 2001; Baumann and Tillman 2004; ISO 2006). The combination of a quantitative approach and a holistic perspective leads to trade-offs being clearly stated in LCA. It is a systems tool well-suited for environment decision making.

Referred to by many names through its development (Baumann and Tillman 2004), LCA has in the last four decades evolved from the idea of cumulative resource requirements into a scientific field that includes emission inventory methods (Heijungs and Suh 2002) and environmental cause-consequence modeling (Udo de Haes, Finnveden et al. 2002). Many of the first applications, including the first Norwegian use of the life-cycle concept (Nunn 1980), were related to beverage packaging, although early reviews show a large span in the products that were assessed with life-cycle approaches (Nord 1992).

The problem of including all significant processes in life-cycle inventories is a well known in LCA (Norris 2002). Hybrid approaches have been proposed as a method to identify the largest contributing paths and to ensure that all processes are included within the system boundaries (Suh 2004; Suh, Lenzen et al. 2004). Hybrid approaches link process information collected in physical life-cycle inventories with monetary flows in economic models. The combination of LCA and input-output models has shown value as a complementary tool to traditional inventory methods in LCA (Heijungs and Suh 2002; Strømman 2005; Strømman, Solli et al. 2006).

Standardization of LCA methodology has been achieved step by step. The SETAC working groups (e.g., Consoli, Allen et al. 1993; Barnthouse, Fava et al. 1997; Udo de Haes, Finnveden et al. 2002) and other institutions have been vital in this process (e.g., Nord 1992; Nord 1995). The development of international standards has been an important driver for defining the methods of LCA. The first set of standards were published by the International Organization for Standardization in 1997 (ISO 1997), with a revised version complete in 2006 (ISO 2006). For a more thorough description of the historical development of LCA, see Ayres (1995) and Baumann and Tillman (2004).

General framework

The standardized framework for LCA states four consecutive stages, as illustrated in Figure 1 (ISO 2006). The stages are described in some detail here, but the reader is referred to guidelines and textbooks for a thorough introduction (e.g., Wenzel, Hauschild et al. 1997; Hauschild and Wenzel 1998; Guinée 2001; Heijungs and Suh 2002; Baumann and Tillman 2004; ISO 2006).

Goal and scope

The first stage of LCA consists of defining the aim and boundaries for the assessment, and the choice of methods for inventory and impact assessment.

The goal and scope stage includes defining the functional unit (FU). The functional unit is a quantitative measure of the functional requirement(s) that the product or service is designed to fulfill. It is the basis for comparison in LCA, used to evaluate the relative performance of alternative product systems.

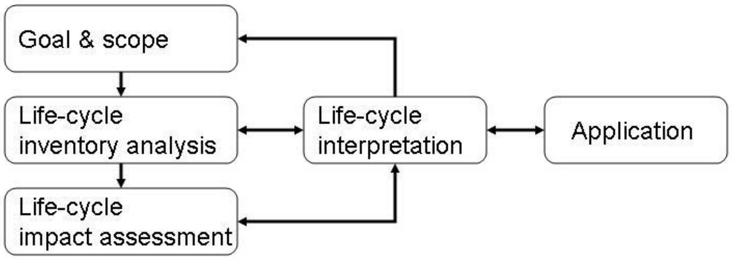

Figure 1: Outline of the stages and iterative approach of life-cycle assessment. (Redrawn from ISO 2006)

Examples of FUs are *15 years of person transport* for transportation systems, *100* m^2*·years* for paints and other surface protectors, and *1 GJ at consumer* for energy supply and distribution systems.

Life-cycle assessment may be applied for various purposes, such as product benchmarking, product declaration, process development and policy support. Study designs set important limitations on the applicability of the study to provide answers. An important issue in this respect is the functional unit. Other issues include the level of inventory completeness, temporal and spatial considerations, and impact and inventory assessment approaches.

Limitations in scope may be caused by resource constraints. Spatial and temporal limitations may be applied to suit policy perspectives. Similarly, a study may be undertaken to investigate a few issues of concern, such as energy efficiency rates or CO_2-equivalents, or it may aim at a broad impact assessment. While limitation of the scope is a necessary step towards completing any study, it is vital that the principle of reproducibility is maintained; i.e., that the eventual limitations do not exclude information that may alter the conclusions.

Life-cycle inventory analysis (LCI)

The second stage consists of establishing an inventory that describes the environmental interventions that arise from the product system. Environmental interventions are inputs of resources from the environment to the product system (i.e., energy and material resources), and outputs to the environmental of adverse effect that the product system produces (i.e., emissions). The inventory is balanced to the functional unit.

Life-cycle impact assessment (LCIA)

Once the inventory of environmental interventions is established, the interventions are translated to environmental impact indicators in the third stage of LCA.

The ultimate purpose of LCA is to provide indication of environmental impact potential. Quantitative scores are achieved by application of characterization factors that describe the relative potential of each intervention to adversely affect safeguard objects through defined impact mechanisms. An example is CO_2-equivalents which are used to aggregate the global warming potential of various emissions to air. Each substance is characterized by its potential relative to the global warming potential of CO_2.

The life-cycle impact assessment stage is divided into three consecutive steps. First, environmental interventions are separated according to their cause-and-effect chains, termed impact chains or impact categories in LCA. Interventions may be input-related; i.e., energy and material extracted from the environment, or they may be output-related; i.e., emissions made to the environment. Second, impact scores are aggregated for each impact category by multiplying inventory mass flows with their respective characterization factors and summarizing for each of the impact chains. The last step of life-cycle impact assessment is the weighting of impact scores relative to each other. Weighting requires relative comparison of different environmental issues; such as comparison of acidifying air-emissions with consumption of material resources. An inherently subjective process, and a voluntary step in life-cycle impact assessment, weighting is not often applied in the scientific literature.

Weighting methods and the selection of impact categories to be considered in an LCA depend on the stakeholders to the study. Identification of stakeholder attributes, and the matching of these with the results produced by the study, is vital to ensure the relevance of any LCA.

Life-cycle interpretation

The final stage of LCA is the interpretation of results. Vital in the interpretation stage is the consideration of uncertainty. Other aspects include the effect and validity of the selected impact assessment methods to fulfill the stated purpose of the study, and the potential bias introduced by inventory sources and approach. The re-visitation of methodological choices validates the outcome of LCA and increases the relevance of LCA for decision support.

Reiteration of goal and scope, inventory and impact assessment stages is an important feature of LCA, as outlined in Figure 1.

Life-cycle impact assessment

Attributes for decisions analysis by LCA are the environmental impact category indicators used in life-cycle impact assessment (Hertwich and Hammitt 2001b). Category indicators are quantitative scores for the relative potential to cause adverse effect through a predefined impact chain. Indicators are made for each impact chain on the basis of a model that relates stressor (i.e., the intervention) to environmental consequence.

Attributes may be defined at various levels of the cause-consequence chain. If defined at the level of value lost, they generally are referred to as endpoint indicators. Attributes defined at intermediate levels in the cause-consequence chain are midpoint indicators in LCA (Hertwich and Hammitt 2001b; Udo de Haes and Lindeijer 2002).

Several cause-consequence models have been developed within the LCA framework, covering a wide set of impact mechanisms (Guinée 2001; Udo de Haes, Finnveden et al. 2002). Table 1 lists a few impact chains for which characterization factors have been developed, divided by their area of protection (Udo de Haes, Jolliet et al. 1999; Guinée 2001). Impact chains frequently relate to more than one area-of-protection due to the inter-related nature of environmental effects, better described as impact webs (see, e.g., Udo de Haes, Jolliet et al. 1999; Hertwich and Hammitt 2001a).

Models of various resolution and complexity have been used in life-cycle impact assessment. For the example of toxic impacts, impact assessment models may be the application of simplistic assumptions regarding environmental residence times and toxicity thresholds (e.g., Hauschild and Wenzel 1998), or more complex representations of model (like the human toxicity potential, Hertwich, Mateles et al. 2001). Continuing with the example of toxic impacts, the impact assessment framework characterizes the relative ecotoxicity of a substance as follows

Equation 1: $S_i^{m,n} = M_i^n F_i^{m,n} E_i^m$

where *S* is the impact score for the ecotoxicity of substance *i* to environmental (recipient) entity *m* through impact chain *n* (i.e., exposure pathway or mechanism). Factors to the right side of the equation are *M*: the amount of intervention (mass loading for ecotoxicity), *F*: the exposure that results from a unit of intervention (fate factor describing the relative distribution to impact chain *n* for ecotoxicity), *E*: dose-response function (ecotoxic effect factor for impact chain *n* for ecotoxicity). The cause-and-effect chain for each final impact chain *m* thereby consists of the following steps for a midpoint indicator for ecotoxicity

Equation 2: $\{\ intervention_m \xrightarrow[\text{Exposure model}]{} \Delta exposure_{m,n} \xrightarrow[\text{Dose-response model}]{} \Delta stress_{m,n}\ \}_i$

Table 1: Impact categories in LCA organized by areas-of-protection. The list is not exhaustive.

Area of protection - societal value(s)	Impact categories (chains/pathways/midpoints)
Natural environment - intrinsic value (ecosystems, species) - life support functions	Depletion of biotic resources Impacts of land use Climate change Ecotoxicity Acidification ...
Natural resources - economic and intrinsic values - life support functions	Depletion of abiotic resources Depletion of biotic resources
Human health - intrinsic value of human life, economic value	Human toxicity Stratospheric ozone depletion Climate change Noise Accidents ...
Man-made environment - cultural, economic and intrinsic values	Loss of materials Loss of catch , crops

Toxicity potentials have been derived for various environmental recipients covering aquatic, sediment and soil compartments and the human population (Hauschild and Pennington 2002; Krewitt, Pennington et al. 2002). The framework outlined in Equation 1 offers midpoint indicators, indicative of the stress induced upon environmental recipients as a result of an environmental intervention. Stress may be translated to damage by use of damage models, thereby continuing the cause-consequence chain from intervention to final endpoint damage.

A common damage indicator for human health in life-cycle assessment is disability adjusted life years (DALY). Originally developed for health economics (Murray and Lopez 1996), DALY is used as endpoint indicator to make commensurable effects from a diverse set of cause-consequence chains including ionizing radiation (Frischknecht, Braunschweig et al. 2000), toxic exposure including effects on the respiratory system and by carcinogenic and noncarcinogenic toxicity (Hofstetter 1998; Pennington, Crettaz et al. 2002; Crettaz, Pennington et al. 2003; Huijbregts, Rombouts et al. 2005), road noise (Müller-Wenk 2004) and occupational health damage (Hofstetter and Norris 2003).

Endpoint metrics are useful for interpretation of life-cycle inventories as they provide a common scale that encompasses several cause-consequence chains. Reducing the number of categories in impact assessment, endpoint metrics lead to easier identification and comparison of trade-offs. Secondly, endpoint indicators may be better representatives for the decision objectives (Hertwich and Hammitt 2001a). Returning to the example of human toxicity, midpoint indicators for human toxicity are extracted from exposure limit values, derived from laboratory test programs or epidemiological surveys (Hofstetter 1998; Huijbregts, Thissen et al. 2000; Hertwich, Mateles et al. 2001). Implemented in LCA they are indicative of the relative potential to cause human toxic effects, but they do not quantify the absolute damage caused by emissions. The DALY framework allows quantification of health burdens in life quality years, a scale to which most people may relate, thereby making results from LCA more understandable (Hertwich and Hammitt 2001a). Such absolute indicators may be important if environmental benefits are compared to other attributes of the system (Hertwich and Hammitt 2001b).

While indicators related to damage may better communicate the scale of impacts, the damage assessment also adds an additional layer to the impact assessment model. The additional modeling of the cause-consequence chain introduces new sources of uncertainty which may blur the comparison of product systems. Product systems that are discernable on midpoint level of impacts may become indiscernible if impacts are quantified in terms of damage (Lenzen 2005).

Life-cycle assessment as industrial ecology

An often quoted definition of industrial ecology states that it is *"the study of flows of materials and energy in industrial and consumer activities, of the effect of these flows to the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources"* (White 1994).

White's definition of industrial ecology carries three aspects: *flows*, the *effect* of the flows to the environment, and societal factors that *affect* such flows. Although not overlapping on all the issues, life-cycle assessment is a tool well defined within the industrial ecology tool box. Life-cycle assessment covers flows between the economical and environmental systems as environmental interventions in the life-cycle inventory (Udo de Haes and Lindeijer 2002), and the life-cycle perspective ensures that inter-industry flows as well as environmental interventions are included within the assessment perspective. Life-cycle assessment therefore produces a comprehensive inventory of the environmental interventions that occur from a product system. Ayres (1995) points out that life-cycle inventories are not comprehensive from a principle of mass conservation and that this practice may lead to results that overlook important impacts. Nonetheless, life-cycle inventories should be comprehensive from the perspective of environmental effects.

Impact assessment is the translation of flows to environmental impact indicators. With some exceptions, notably acidification, eutrophication and certain substances with respiratory effects; see summary in (Potting, Klöppfer et al. 2002), life-cycle impact assessment generally does not incorporate the element of thresholds and spatial variation. Impacts are proportional functions of environmental interventions independent of emission pattern and temporal and spatial considerations. The focus lies on the investigation of flows themselves rather than the assessment of effects that flows may cause. The main reason is the wide assessment perspective of LCA, as emissions are aggregated across temporal and spatial scales.

The aspect of change is not strongly emphasized in LCA, although recently several studies have assessed net effects that occur from choices made in system design and development (see, e.g., Jungbluth, Bauer et al. 2004; Fehrenbach 2005; Ekvall and Andræ 2006; Eriksson, Finnveden et al. 2007; Sandén and Karlström 2007). Such studies are referred to as consequential LCA or change-oriented LCA (Ekvall 2002; Curran, Mann et al. 2005; Sandén and Karlström 2007). The traditional, attributional LCA describes the environmental performance of product systems as attributes of the product system design, relying on the use of average data for materials and energy. Marginal data becomes more relevant if change of system designs is assessed with LCA. Marginal situations are functions of the time perspective, market flexibility and trends, and the level of market influence (Ekvall and Weidema 2004). Examples of consequences playing a role in LCA are if former waste fractions become resources, thereby replacing parts of an existing resource system, or changes in energy systems which may have system-wide effects. In the first example, waste oils may be regenerated to replace virgin oils. If the composition of the virgin oil is expected to change over time, assessments should include the effect that such changes have on the performance of the original virgin system that is replaced (see, e.g., Fehrenbach 2005). A second aspect of change-oriented LCA is that boundaries may need to be expanded to include several functions (Ekvall and Weidema 2004). Waste oils may be used as an energy source or it may be regenerated. By selecting one of the life-cycle alternatives, the consequence is that the function not provided by waste oil is replaced by either energy or virgin oil given a system of constant demand.

While factors affecting environmental interventions may be discussed in LCA, the implementation of external factors is not part of the traditional approach. Changes in regulations, trends and policy are generally considered outside of the scope of LCA. Used to support inventory generation, external factor analysis increases the relevance of LCA as policy support, but it is a complementary approach for sensitivity analysis rather than an intrinsic part of LCA.

Life-cycle assessment as systems analysis

Findeisen and Quade (1985) divide decision making into the following three main elements. First are the alternatives under consideration. In the context of this thesis, alternatives are the options for consideration by comparative LCA. Second are objectives, attributes and criteria, linked together as follows: Objectives are the desires of the decision maker, uttered or implied. The objectives are translated to quantitative measures as either functional requirements (i.e., constraints) which must be met, or attributes on which the performance of alternatives is measured. Criteria are the rules or standards by which the attributes are ranked relative to each other, identical to the framework of characterization factors and weighting schemes in LCA. The third element in decision making is the model that allows us to investigate performance of alternatives on the attributes that are selected. The model that we describe here is the method of life-cycle assessment.

The selection of performance measures constitutes an important part of systems analysis. Performance measure definition should be part of the early stage of projects (ISO-IEC 2002). Various terms have been proposed to separate classes of performance measures in systems engineering (Oliver, Keliher et al. 1997; Stevens, Brook et al. 1998). Keeping with the terminology of Findeisen and Quade (1985), we divide performance measures into *constraints* on the system and *attributes* of the system. Constraints describe the limitations within which solutions must be found, while attributes are the measures used to rank the alternatives.

With reference to LCA, constraints include the functional unit and the industrial and societal environment in which the product system operates. Systems are not brought into being unless in agreement with the boundaries of the constraints (Sproles 2000). Economical constraints, often the constraint deciding the design, may show properties of elasticity. In common systems engineering approaches, economical performance therefore forms part of the attributes of a system. In environmental assessments, however, economical issues are considered constraints on the system design. Optimizing on economy may produce non-dominant solutions for the environmental attributes. Physical and technical constraints affect the viability of system installment. Physical space limitations are very important for rig technology given the limitations in floor area. Technical constraints include system reliability, availability and possible risk aspects.

Regulatory constraints include standards, policy and acts of law, all of which must be met for any technology used offshore and elsewhere. Other constraints are, e.g., environmental image and company policy.

Attribute measures are consequences of the physical design of systems. For the case of LCA, attributes constitute a set of environmental impact indicators. In order to be useful for decision support, the results provided by LCA must match with the objectives posed by stakeholders, and be representative of objective performance. They must also carry an aspect of measurability (Keeney 1992; Hertwich and Hammitt 2001a).

It is important to consider problem shifts when implementing environmental policy (Wrisberg, Udo de Haes et al. 2002). Life-cycle assessment includes processes from cradle-to-grave and covers a potentially large number of environmental impact chains. It is therefore well-suited to identify problem shifts between life-cycle stages, recipients, effects and temporal locations. However, life-cycle assessment is inherently function-oriented, not region-oriented (Olsen, Christensen et al. 2001; Wrisberg, Udo de Haes et al. 2002). Shifts due to variation in environmental sensitivity may therefore go undetected because only generic environments are considered.

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