ELSEVIER

Journal of Hazardous Materials 61 (1998) 23–29

JOURNAL OF HAZARDOUS MATERIALS

# A risk-based approach to life-cycle impact assessment

Jan A. Assies *

*Center for Energy and Environmental Studies, University of Groningen, P.O. Box 72, 9700 AB Groningen, Netherlands*

**Abstract**

This paper suggests an approach to life-cycle impact assessment which is based on the comparison of predicted exploitation or pollution levels with critical levels; the latter representing the carrying capacity of the commodity-supplying or pollutant-receiving environment. The incremental pressure induced by the product system is weighted with the total pressure on the reference environment. Geographic dimensions of the reference environment are chosen in accordance with the spatial sphere of influence of commodity extractions or pollutant emissions. The feasibility of the approach is shortly surveyed for a number of input-related and output-related impacts and the approach is compared with conventional life-cycle impact assessment. It is concluded that life-cycle *risk* assessment may contribute to a better harmonization of methods for impact assessment. © 1998 Elsevier Science B.V. All rights reserved.

*Keywords:* Life-cycle assessment; Life-cycle impact assessment; Risk assessment; Sustainable development

## 1. Introduction

Life-cycle assessment (LCA) is an emerging decision-support tool which is aimed at a systematic assessment of the environmental performance of product systems, from raw material acquisition to final waste disposal. Until now, most attention was paid to the life-cycle inventory, the component of the study in which a model of the product system is developed and its material and energy inputs and outputs are reported. The next component of LCA, life-cycle impact assessment, is being developed to provide improved insight in the environmental relevance of the inventory results.

The historical development of LCA led to conventions for the life-cycle inventory—relating inputs and outputs of the same substance to a functional unit—which appear to

* Present address: Heresingel 22, 9711 ET Groningen, Netherlands.


*PII* S0304-3894(98)00103-4

be a severe limitation to the possibilities for reliable impact assessment. Data aggregation on the basis of a functional unit *removes* temporal and spatial dimensions from the inventory data, whereas an evaluation in the light of sustainable development *requires* temporal and spatial detail. Commodity extractions or pollutant emissions will only contribute to adverse effects if the total rate of extractions or emissions (= incremental + background) exceeds the carrying capacity of the environment. Flow rates are therefore more sensible parameters for impact assessment than quantities per functional unit. Spatial information is important because many of the extracted commodities or emitted pollutants are not evenly traded or distributed over the globe. Impact assessment should therefore take account of geographic differences in fate factors, background levels and sensitivity of the commodity-supplying or pollutant-receiving environment.

This paper presents an approach to life-cycle impact assessment which is similar to—and compatible with—procedures for non-probabilistic risk assessment. The method is based on a comparison of predicted exploitation or exposure levels with critical levels. Answers are sought to the following questions which are considered to be important for environmentally benign decision-making: (1) Is it likely that the product system contributes to actual harm? and, if so, (2) what is the total stress on the endangered element(s) of the environment? and (3) how much does the product system contribute to it? The approach yields risk indicators representing the environmental performance of the product system per impact category. If the study is aimed at a comparison of product systems, it is also possible to assign risk indicators to a functional unit, in a step following the calculation of risk indicators for the system as a whole.

## 2. The model of the product system

As a first tier approach to integrate a temporal dimension with the life-cycle inventory, it is assumed that the product system is a system in steady state. Inputs and outputs of the system are related to a realistic estimate of the annual production or consumption of the product or service under review. Extractions from and emissions to the environment are expressed as annually averaged flow rates. The model of the product system can be tailored to the type of product under review. One possibility is to make a ‘cross section’ through the system in a given year. Another possibility is to make a ’longitudinal section’ and to follow the annual production of one year with different years attached to the stages of the life-cycle.

The output of the model comprises annually averaged inflows to the product system and outflows to the various environmental compartments. Inflows and outflows bear a geographic label. Dependent on the availability of site-specific or market-average data, the geographic label will be more or less specific.

## 3. Impact categories and subcategories

Impact categories in LCA are usually defined on the basis of issues of general concern in the environmental debate: resource depletion, climate change, stratospheric ozone depletion, acidification, effects of toxic releases, etcetera. A requirement for accurate data aggregation during the impact assessment phase, is the definition of homogeneous impact categories. Resources within the same category should, to a reasonable extent, be interchangeable as for their societal and/or ecological function; pollutants within the same category should, to a reasonable extent, be interchangeable as for their effect on specified elements of the environment. The need for data aggregation —and consequently the need to define homogeneous impact categories—depends on the type of application of the study results. The need for condensed data will usually be high if the study is used to support a comparative assertion (on the basis of the same functional unit); the need for condensed data will usually be low if the study is used to avoid the risk of adverse effects.

Some impact categories should be divided into subcategories to take account of differences in the mobility of pollutants which contribute to the same effect; the spatial scale of the reference environment should, to a reasonable degree, reflect the geographic sphere of influence of pollutant emissions which are assigned to the same (sub)category. Similarly, main categories for resource use may be divided in subcategories to take account of differences in trade distance of extracted commodities.

For some emission-related categories it may be relevant to make a subdivision on the basis of temporal spheres of influence of pollutant emissions, in order to prevent the loss of useful information. The type of indicators which are suggested in this paper (based on steady-state models) are sensitive to a high persistency (eventually leading to high exposure levels) and to a high potency of pollutants (connected to a low critical level); the indicators themselves, however, do not differentiate between the two possibilities.

## 4. Screening

In the first step of life-cycle risk assessment are geographically labeled inventory data assigned to impact categories or subcategories and related to geographically corresponding reference environments. The commodity-supplying or pollutant-receiving environment is depicted by characteristic pollutant-transfer coefficients (to model the emission-exposure relation), its sensitivity to depletion/pollution (critical load or level) and background depletion/pollution. Reference environments are based on steady-state, mass-balance, calculations; they can be modeled with different degrees of precision, ranging from generic to site-specific.

To discriminate between activities which are likely to contribute to actual harm and activities which are likely to be harmless, a screening is performed using the value of the total load/critical load quotient, also referred to as risk quotient (RQ), connected to the reference environment. Risk quotients are compared with predefined thresholds ($T$). Activities may be classified in a safe zone (green: $\mathrm{RQ} \leq T$), a hazard warning zone (yellow: $T < \mathrm{RQ} \leq 1$) and a critical zone (red: $RQ > 1$).

Risk quotients are not specific to LCA and may be derived from risk-based research focused on the various issues of concern. For regional and higher scale assessments, it is usually reasonable to assume a marginal contribution of the product system to the total load. Risk quotients may then be calculated independent of the individual LCA study and the information may be presented in risk maps.

## 5. Assessing the incremental pressure in relation with the total pressure

Risk quotients can be viewed as measures representing the total pressure on (a) specific element(s) of the environment. Similarly, we can calculate incremental load/critical load quotients which represent the incremental pressure induced by the product system. It is however, not logical to attach the same weight to an incremental load which coincides with a total load well below the critical level and an equal incremental load which coincides with an exceedance of the critical level. Therefore, two formulations are used which link the incremental pressure to the total pressure on the reference environment.

Risk indicators represent the incremental pressure of the product system *weighted with* (multiplied by) the total pressure on the reference environment. Risk indicators per reference environment $i$ are calculated according to:

$$I_i = \text{incremental pressure} \times \text{total pressure} = \sum_x \frac{l_{\text{incr};x,i}}{L_{\text{crit};x,i}} \times \sum_x \frac{L_{\text{tot};x,i}}{L_{\text{crit};x,i}}, \quad (1)$$

where $l_{\text{incr};x,i}$ is the incremental load of substance $x$ for reference environment $i$. For commodity extractions, $l_{\text{incr};x,i}$ represents the incremental extraction of substance $x$ from reference environment $i$. Emissions of substance $x$ from source $k$ are translated into the incremental load through the application of a transfer coefficient $K_{k,i}$, which is derived from the same fate and exposure model which is used to calculate the total load, thus: $l_{\text{incr};x,i} = K_{k,i} e_{\text{incr};x,k}$. Risk indicators may be added up over spatially or temporary separated reference environments to arrive at a total score per impact category.

Risk indicators of Eq. (1) do not differentiate between a large contribution of the product system and a large overall pressure. If the incremental pressure is not multiplied but divided by the total pressure, we additionally get a measure of the proportional contribution of the product system to the total pressure on the reference environment.

## 6. Conclusions

Table 1 summarizes some findings of an initial survey of the feasibility of life-cycle *risk* assessment; case studies have to be performed to further investigate its feasibility [1]. The framework for life cycle risk assessment has several advantages as compared with conventional life-cycle impact assessment [2]. Amongst others:

- Life-cycle risk assessment links LCA to the ultimate goal of sustainable development. A clear distinction is made between sustainable and non-sustainable use of the life-support functions of our environment. Conventional LCA does not make this distinction and may even direct the decision-making process towards a choice for the most harmful alternative. A higher score for ‘potential impact’ within conventional LCA

Table 1
Some environmental issues and the possibilities for life-cycle risk assessment

| Issue | Homogeneous category? | Subcategories | Output of fate model | Critical level |
|---|---|---|---|---|
| Depletion non-renewables | no | spatial | – | reserve divided by respite time |
| Depletion renewables | no | spatial | – | annual surplus production |
| Climate change | yes | spatial temporal | radiative forcing; equivalent $CO_2$ | stabilization level; budget divided by respite time |
| Stratospheric ozone depletion | yes | temporal | equivalent effective stratospheric chlorine | pre-ozone hole level of EESC |
| Acidification | yes | spatial | acid deposition | critical load (deposition) |
| Human toxicity | no | spatial | predicted exposure | predicted no-effect level |
| Ecotoxicity | yes (?) | spatial | predicted exposure | predicted no-effect level |

does not automatically imply more environmental harm. Usually, the latter depends on temporal and spatial characteristics which are removed in the life-cycle inventory. Conventional LCA may therefore easily misguide improvement measures or policy making [3].

• Life-cycle risk assessment provides a clear decision rule—based on environmental relevance—to decide which inputs and outputs to or from the product system should be studied. The lack of temporal and spatial information of conventional LCA obstructs a sensible (threshold-) screening. The International Standardization Organization concludes that current decision rules, usually based on mass, may lead to major omissions [4].

• Life-cycle risk assessment allows a meaningful assessment of potential impacts other than global warming and stratospheric ozone depletion. Conventional LCA applies 'equivalency factors' or 'characterization factors' to the aggregated inventory data, yielding impact scores for 'potential impacts'. However, 'equivalency factors', which have been suggested for impacts other than global warming and stratospheric ozone depletion, are scientifically unjustified, resulting in a crippled relation between impact scores and potential impacts. Drafts for the International Standard concerning Life-Cycle Impact Assessment therefore rightly restrict the public use of conventional life-cycle impact assessment for comparative assertions to the impact categories global warming and stratospheric ozone depletion [5].

• Life-cycle risk assessment allows a consistent and transparent assessment of the range of impacts normally addressed in life-cycle impact assessment using indicators of the same design; new issues of concern might be included. The 'equivalency factors' used in today's LCAs are based on various, even contradicting, principles. This inconsistency means a loss of transparency and makes a proper interpretation of the resulting impact profiles a precarious, if not impossible, task. The need to remove inconsistencies from current practice is well recognized [6].

• Life-cycle risk assessment allows the evaluation of marginal and non-marginal contributions of the product system to particular impacts. It is generally assumed that the validity of conventional life-cycle impact assessment—if it is valid at all—is limited to marginal contributions of the product system to particular impacts.

• Life-cycle risk assessment allows a clear communication of value-based choices, simplifying assumptions and uncertainties. It is recognized that decisions must be made even when understanding is imperfect; value judgements and simplifying assumptions can not be avoided. The conventional approach to life-cycle impact assessment rather disguises value judgements, simplifying assumptions and uncertainties with pseudo-science than revealing them, which is opposed to the need for transparency [7].

• Life-cycle risk assessment allows inclusion of more temporal detail without the need to change the entire framework. Uncertainty analysis of initial study results may reveal that more temporal detail is required to support the decision at hand. Of course are the modeling assumptions of a steady-state product system (on the basis of its annual turnover) and a steady-state environment rather rough simplifications of reality. However, an initial assessment on the basis of a simple model and conservative assumptions provides a clear basis for evaluation and, conceivably, for further assessments, focused on the issues of greatest concern. The latter may range from assessments over a shorter interval of time or probabilistic risk assessment to long-term assessments on the basis of scenario studies.

• Life-cycle risk assessment allows inclusion of more spatial detail without the need to change the entire framework. Uncertainty analysis of initial study results may reveal that more spatial detail is required to support the decision at hand. Assessment within the framework may range from generic to site-specific.

• Life-cycle risk assessment is compatible with other tools for resource and environmental assessment. Conventional LCA is not compatible with risk assessment and environmental impact assessment [8–10]. Incompatibility of LCA with other tools which may be used to support the same decision, may rather confuse the decision-making process than support it. Harmonization of tools for impact assessment is therefore an urgent demand.

It is concluded that a scientifically sound and/or policy relevant assessment of non-global impacts requires fundamental changes within the current setup of the life-cycle inventory; data aggregation on the basis of a functional unit should be postponed to a later stage of the study. Life-cycle *risk* assessment may contribute to harmonization of terminology and methods of the various fields of science that meet each other in life-cycle impact assessment. It is a major challenge to the LCA-community to facilitate improved communication of environmentally relevant information between scientists of different disciplines and between scientists and decision makers.

## References

[1] J.A. Assies, Risk indicators for use in Life-Cycle Impact Assessment: an approach based on sustainability, IVEM, Center for Energy and Environmental Studies, University of Groningen, Netherlands, 1997, in preparation.

[2] Udo de Haes, H.A. (Ed.), Towards a methodology for life cycle impact assessment, Report of the SETAC-Europe working group on Life Cycle Impact Assessment, SETAC-Europe, Brussels, Belgium, 1996.

[3] P. White, B. de Smet, H.A. Udo de Haes, R. Heijungs, LCA back on track: but is it one track or two?, SETAC-Europe LCA News 6 (3) (1995) 2–4.
[4] ISO (International Standardization Organization), Environmental management—life cycle assessment—goal and scope definition and inventory (Committee Draft ISO/CD 14041.2), ISO Technical Committee 207 on Environmental Management, Subcommittee 5 on Life Cycle Assessment, Document No. ISO/TC207/SC5N82, Paris, France, 1996.
[5] ISO, Environmental management—life cycle assessment—life cycle impact assessment (Committee Draft ISO/CD 14042.1), ISO Technical Committee 207 on Environmental Management, Subcommittee 5 on Life Cycle Assessment, Document No. ISO/TC207/SC5N97, Paris, France, 1997.
[6] Finnveden, G., L.-G. Lindfors, Life-cycle impact assessment and interpretation, LCANET theme report, LCANET, European Network for Strategic Life-Cycle Assessment Research and Development, Stockholm, Sweden, Leiden, The Netherlands, 1997.
[7] R.J. Perriman, Is LCA losing its way?, SETAC-Europe LCA News 5 (1) (1995) 4–5.
[8] Udo de Haes, H.A. (Ed.), Towards a methodology for life cycle impact assessment, Report of the SETAC-Europe working group on Life Cycle Impact Assessment, SETAC-Europe, Brussels, Belgium, 1996.
[9] SETAC (Society of Environmental Toxicology and Chemistry), Life cycle impact assessment: the state-of-the-art, Report of the SETAC LCA Impact Assessment Work Group, Society of Environmental Toxicology and Chemistry, Pensacola, FL, USA, 1997.
[10] J.W. Owens, Life-cycle assessment in relation to risk assessment: an evolving perspective, Risk Anal. 17 (1997) 359–365.