LIFE CYCLE IMPACT ASSESSMENT
A BRIEF SURVEY WITH SOME IDEAS ON RADIATION

Reinout Heijungs
CML (Centre for Environmental Science, Leiden University)
P.O.Box 9518, 2300 RA Leiden, The Netherlands
phone: (+31)-71-277486, telefax: (+31)-71-277496

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Abstract
It is argued that life cycle assessment (LCA) is an important tool for the analysis or comparison of alternatives delivering the same function, such as systems for energy generation. A brief survey of the operationalization of a number of impact categories is given: for global warming, acidification and human toxicity, now and in the future. It is observed that radiation is a very underdeveloped impact category in LCA. The ideas of these principles is used to state some ideas on the way towards the inclusion of impacts of radioactive decay in LCA. The main conclusion is, however, that a further elaboration of an environmental impact indicator for emissions is essential for a fair analysis, comparison, and judgment of alternatives.

LCA and problem shifting

When comparing the environmental impacts of a number of activities, processes or products, the activities themselves have to be defined. This involves at least two aspects:

- the basis of comparison;
- the system boundaries.

These two points will be illustrated by examples.

One could compare a bicycle with a car, as two products. A better idea is, however, to compare these products on a functional basis, e.g. daily commuting transport over 5 kilometre.

One could compare using the bicycle with using the car. Another relevant option could be to include not only the use of these products, but also production, maintenance and final disposal.

Using the functional basis of comparison, and including the broad system view "from cradle to grave" amounts to what is generally known as environmental life cycle assessment of products, or, in short, LCA. The general idea of LCA is the analysis of a function fulfilled by a product, or the comparison of several products that fulfil the same function, trying to take into account all environmental impacts in all life cycle stages.

A typical question which can be answered with LCA is, whether fluorescent lamps are better than ordinary incandescent lamps. The following table illustrates the complexity of the analysis of all environmental impacts in all life cycle stages.

property	incandescent lamp	fluorescent lamp
power consumption	60 W	18 W
life span	1000 hr	5000 hr
mass	30 g	540 g
mercury content	0 mg	2 mg

The power consumption of the fluorescent lamp is much lower, and its life span much longer. But

this is to some extent compensated by the fact that it has a higher mass, and thus requires more natural resources. Moreover, more trucks are required to transport 1,000,000 lamps, and these lamps contain a toxic substance.

The reason for considering all impacts and all stages is the avoidance of problem shifting. Amongst others, the following types of problem shifting exist:

- to other life cycle stages (e.g. electric cars avoid emissions during use by causing emissions before use);
- to other impacts (e.g. nuclear energy avoids acidification but creates radiation problems);
- to other environmental media (e.g. flue gas filters decrease air pollution but are dumped after use);
- to other locations (e.g. chemical waste can be exported to other countries);
- to future generations (e.g. dumping nuclear waste in the oceans creates future problems).

LCA takes into account not only all impacts and all life cycle stages, but also is about resources, air, water and soil; it ignores national borders, and it has an infinite time horizon. This makes it a good instrument for an integrative assessment of the environmental consequences of economic activities, without provoking the risk of problem shifting.

More specific within the field of the analysis of energy generation, it can be noticed that LCA is more and more being used (Van Engelenburg & Nieuwlaar, 1993; Frischknecht *et al.*, 1993).

It should be noticed that LCA is a methodology for the generic analysis or comparison of activities. A typical question is: "What is generally better: an incandescent lamp or a fluorescent lamp?". LCA is thus opposed to environmental impact assessment (EIA), which is about one specific well-defined activity. It may be so that fluorescent lamps are better in general, but that this very fluorescent lamp factory is for some reasons not very good, just because it is situated on the wrong site. It could even be that every fluorescent lamp factory is worse than every incandescent lamp plant, but that this is compensated by a cleaner use phase.

A framework

The example on incandescent and fluorescent lamps indicates the complexity of the problem. The table with relevant properties is, of course, much longer, and so diverse, that it is almost impossible to interpret and use it for decision making. Therefore, another way of representing the problem is required. This can be found in an analysis in terms of the system's constituent processes. The life cycle of a product consists of different processes: extraction of resources, production of materials, transportation, use, maintenance, waste treatment (including recycling), etc. All these processes have a number of inputs and outputs. These inputs and outputs can be of two types:

- economic input and outputs (e.g. PVC, electricity or transportation);
- environmental inputs and outputs (e.g. crude oil, SO_2 or noise).

By following the life cycle, one eventually "translates" all economic inputs and outputs into environmental inputs and outputs. One thus performs a system analysis, and keeps track of the inputs from and the outputs to the environment.

LCA is a rapidly developing field of research. The *Society of Environmental Toxicology and Chemistry* (SETAC) is the leading international forum in which researchers discuss the progress of LCA. An important milestone with respect to harmonization of methods is last year's publication of a *Code of Practice* (Consoli *et al.*, 1993). This is not a method for LCA, but it provides a broadly accepted framework and terminology. The framework is presented in this paper as the standard one. It consists of four components:

- goal definition and scoping, in which e.g. the basis for comparison of alternatives is chosen;
- inventory analysis, in which a flow-chart of all processes involved in the life cycle is drawn up and the flows of materials and substances are quantified;
- impact assessment, in which the inputs and outputs are aggregated into a limited number of impact categories, and in which a further weighing of these impact categories is made;
- improvement assessment, in which the data collected are used for a systematic search for options for environmental improvement.

Different elaborations of methods which more or less fit in the SETAC-framework exist. The goal definition and scoping is not methodological but mainly a procedural step. The inventory analysis is quite well elaborated, and there is a large amount of agreement (see e.g. Habersatter, 1991; Fava *et al.*, 1991; Heijungs *et al.*, 1992, Vigon *et al.*, 1993). The situation for the impact assessment is quite different. Many impact categories have not yet been operationalized. For other ones, different proposals have been made, and consensus has not yet been achieved. Examples can be found in Fava *et al.* (1993), Heijungs *et al.* (1992) and Finnveden *et al.* (1993). The improvement assessment is the least developed part. The only methodological descriptions we are aware of are Heijungs *et al.* (1992) and Heijungs (1994).

The remainder of this paper will be concerned with the impact assessment component of LCA.

Impact assessment

In the first part of the impact assessment, an aggregation of the environmental inputs and outputs into a number of impact categories is made. Consoli *et al.* (1993) make a distinction between the classification (in which the impact categories are defined and the inputs and outputs are grouped within these categories) and the characterization. Quoting: "Characterization is the step in which [...] aggregation of the impacts within the given impact categories takes place. This step should be based on scientific knowledge about environmental processes."

The other part of the impact assessment is the valuation. Again quoting Consoli *et al.* (1993): "Valuation is the step in which the contributions from the different specific impact categories are weighted [...]. The aim of this step is to arrive at a further interpretation and aggregation of the data of the impact assessment. [...] The importance of the impact categories in relation to each other is a value-bound procedure based on an assessment of the relative environmental harm. This assessment will therefore reflect social values and preferences."

This paper will now concentrate on the issue of characterization.

Characterization

The *Code of Practice* gives the following list of problem categories:

- depletion of abiotic resources;
- depletion of biotic resources;
- global warming;
- ozone depletion;
- human toxicity;
- ecotoxicity;
- photochemical oxidant formation;
- acidification;
- eutrophication;
- degradation of land.

On the basis of Guinée (1992) and Heijungs *et al.* (1992), some items could be added:

- radiation;
- waste heat;
- noise;
- smell;
- occupational health;
- desiccation;
- victims.

It should be observed that energy and waste are not regarded as impact categories. The conversion of natural resources into energy and the treatment of waste are economic processes which should be included within the life cycle. As such, they are directly or indirectly responsible for extractions of resources and emissions of chemicals.

Numerous proposals to define impact indicators have been made. In the next sections, some examples will be elaborated, from simple to complicated. In order to show how they are used in LCA,

they will be applied to an example. The inventory analysis produces a table in which all extractions of resources and all emissions of chemicals are quantified. A simple inventory table is shown below. This is used as an example to demonstrate how the characterization proceeds.

input/output	amount
CO_2 emitted to air	5 kg
CH_4 emitted to air	2 kg
SO_2 emitted to air	0,5 kg
NO_2 emitted to air	0,1 kg

Global warming

The *International Panel on Climate Change* (IPCC) is an international scientific forum, which provides a platform for discussion on the causes and effects of global warming. One of their activities has been the compilation of lists with so-called *global warming potentials* (GWP). The GWP is a measure of the "greenhouse strength" of a greenhouse gas. It is defined as the ratio between the contribution to the heat radiation absorbtion resulting from the instantaneous release of 1 kg of a greenhouse gas and an equal emission of carbon dioxide integrated over time:

$$GWP_i = \frac{\int_0^T a_i c_i(t)\mathrm{d}t}{\int_0^T a_{CO_2} c_{CO_2}\mathrm{d}t} \qquad (1)$$

where a_i is the heat radiation absorbtion per unit concentration increase of a greenhouse gas i, $c_i(t)$ is the concentration of the greenhouse gas i at time t after the release, and T the number of years over which the integration was made. The corresponding values for carbon dioxide are included in the denominator of the equation (Houghton *et al.*, 1991).

Using a time horizon of 100 years – and not going into detail what is the best choice for T – the GWP of CO_2 is (by definition) 1, and 11 for CH_4 (Houghton *et al.*, 1992). This can be interpreted as follows: 1 kg CH_4 contributes 11 times as strong to global warming as 1 kg CO_2. Going back to the inventory table, we have to aggregate 5 kg CO_2 and 2 kg CH_4. It can be argued that the total effect score for global warming amounts to $5\times1+2\times11 = 27$ kg CO_2-equivalent. A more general expression is:

$$GW = \sum_i GWP_i \times m_i \qquad (2)$$

where GW is the total effect score for global warming, m_i is the mass of greenhouse gas i released, GWP_i is its corresponding global warming potential, and i runs over all greenhouse gases. The score GW is expressed in kg CO_2-equivalent.

Acidification

For acidification, the situation is less clear. First, there is not an international forum in which models for acidification are discussed. Second, acidification is – in contrast to global warming – not a global environmental problem. It makes a difference whether a potentially acidifying substance is emitted in a tropical area or in a moderate climate zone. It also makes a difference whether it is emitted off-shore or on a sandy soil.

One particularity of LCA is its global nature: the life cycle of a product is often dispersed over the entire world: the oil comes from Oman, the iron from Russia, production takes place in Taiwan, and consumption in France. Executing LCA would become unfeasible if all site-specific conditions, like climate, soil type, population density, and presence of sensible ecosystems, were to be incorporated. As a baseline, the impact assessment of LCA is, therefore, generally seen as a generic, non-site specific, tool. The consequence of this is, that the impact indicators are about potential risks instead

of actual risks (Heijungs *et al.*, 1992; Heijungs & Guinée, 1993).

A way of assessing the potential impacts of acidifying substances is, to calculate the potency to create H^+-ions. Consider first SO_2: the reaction equation is

$$SO_2 + H_2O + O_3 \rightarrow 2H^+ + SO_4^{2-} + O_2$$

which means that 1 mol SO_2 can create 2 mol H^+. Considering that SO_2 has a molecular mass of 64 $g \cdot mol^{-1}$, we see that 1 kg SO_2 can create 1000/32 mol H^+. For NO_2 the reaction equation reads

$$NO_2 + \tfrac{1}{2}H_2O + \tfrac{1}{4}O_2 \rightarrow H^+ + NO_3^-$$

This implies that 1 kg NO_2 can create 1000/46 mol H^+. Defining, similar to the GWP, a so-called acidification potential (AP), relative to SO_2, the AP of SO_2 is 1 by definition, and the AP of NO_2 0.7. The inventory table gave 0.5 kg SO_2 and 0.1 kg NO_2, so the total effect score for acidification is $1 \times 0.5 + 0.7 \times 0.1 = 0.57$ kg SO_2-equivalent.

More general, the form is

$$A = \sum_i AP_i \times m_i \tag{3}$$

where A is the total effect score for acidification, m_i is the mass of acidifying substance i released, AP_i is its corresponding acidification potential, and i runs over all acidifying chemicals. The score A is expressed in kg SO_2-equivalent.

Human toxicity (provisional method)

For the protection of human health, the *World health organization* (WHO) has compiled lists with so-called air quality guidelines (AQG; Anonymous, 1987). For many toxic substances, AQGs have been determined. They are expressed in $kg \cdot m^{-3}$. Although not intended for use in LCA, they can be applied in an approach which is often called a "critical volumes approach". Neglecting disturbing factors for the moment, such as the fact that some AQG are determined as a 1-hour guideline and others as a 24-hour guideline, it is possible to calculate the amount of air which would be polluted precisely to the AQG with the given amount of substance. E.g. as the AQG of SO_2 is 350 $\mu g \cdot m^{-3}$, and the inventory table shows an atmospheric emission of 0,5 kg SO_2, 1428 m^3 air can be polluted with this amount of SO_2. The AQG of NO_2 is 150 $\mu g \cdot m^{-3}$, which gives a critical volume of 667 m^3 air. The total effect score for human toxicity is thus 2095 m^3 air.

In general:

$$HT = \sum_i \frac{m_i}{AQG_i} \tag{4}$$

where HT is the total effect score for human toxicity, m_i is the mass of toxic substance i released, AQG_i is its corresponding air quality guideline, and i runs over all toxic chemicals. The score HT is expressed in m^3 air.

Human toxicity (intended method)

The approach for toxicity is not very satisfying, as the fate of the chemical is not included. The AQG for mercury is 1 $\mu g \cdot m^{-3}$, but this is based on a constant immission level. As the inventory table shows, LCA is not concerned with immissions, but with emissions. An emission of 1 μg Hg and 150 μg NO_2 would for a short time lead to an equal critical volume. But after while, part of the NO_2 has been degraded, whereas mercury is persistent. Besides degradation, partitioning from water to soil, from air to soil, etc. are other important aspects.

In order to include exposure in a proper way, environmental multi-media models may be applied (Mackay, 1991). These models assume a linear relationship between the emission flux Φ of substance i and its immission concentration C_i as:

$$C_i = K_i \times \Phi_i \tag{5}$$

where K_i is a proportionality factor which depends on a number of model properties (volume of air,

temperature, etc.) as well as on substance properties (octanol-water coefficient, vapour pressure, etc.). One can prove that it is possible to apply these models in LCA (Heijungs & Guinée, 1994). This can be done by introducing a reference substance, e.g.

$$HTP_i = \frac{K_i}{K_{\text{phenol}}} \times \frac{AQG_{\text{phenol}}}{AQG_i} \tag{6}$$

In this way one defines a human toxicity potential (HTP), relative to phenol. Application in LCA proceeds according to

$$HT = \sum_i HTP_i \times m_i \tag{7}$$

where HT is the total effect score for human toxicity, m_i is the mass of toxic substance i released, HTP_i is its corresponding human toxicity potential, and i runs over all toxic chemicals. The score HT is expressed in kg phenol-equivalent.

Ionizing radiation

Ionizing radiation (here referred to as radiation in short) is the least developed impact category in LCA. The best we saw until now is that the amount of radioactive waste is aggregated in kg. Some make a distinction in several categories of radioactive waste. The risks due to calamities is sometimes qualitatively included, as a remark. In literature, some suggestions are given for ways towards improvement (Heijungs *et al.*, 1992; Fava *et al.*, 1993). Due to the absence of a good indicator for radiation, a comparison of e.g. different ways to produce energy is difficult, even with LCA.

Due to the lack of ideas for an impact indicator for radiation, no clear ideas have been formulated until now on how radiation should be specified within the inventory table. Is it sufficient to list kilograms (or becquerels) of a specified isotope? Or do we need information on the energy and type of particles emitted? Below, some very preliminary ideas will be presented. These are ideas are the basis of a more elaborate discussion (Heijungs *et al.*, 1994)

Impacts by radiation can be caused in two ways:

- impacts caused by radioactive substances emitted to the environment, where they decay under the emission of radiation;
- impacts caused by radiation emitted to the environment, without emission of the radioactive substance itself.

These two categories need a separate treatment. We will therefore on an inventory level distinguish between emission of radioactive substances and emission of radiation.

On an impact level another distinction is required:

- impacts caused by internal exposure to radiation, due to intake of food or drinking water, or by breathing;
- impacts caused by external exposure to radiation, due to the presence of radioactive substances somewhere around human beings or ecosystems.

Emissions of radioactive substances can contribute to both internal and external impacts. Emissions of radiation only contribute to external impacts. See the table.

	impact category in characterization	
inventory data	external impacts	internal impacts
emission of radioactive substances	+	+
emission of radiation	+	–

Internal exposure to radiation

Above, we have seen that SO_2 contributes to more than one problem type. It was included fully in acidification as well as in human toxicity. Including it fully twice can be defended by stressing the concept of potential impacts.

Radioactive substances can also contribute to more than one impact category. Plutonium, for example, emits radiation, and it is extremely toxic. It should therefore be treated in the normal way in the impact category human toxicity. This implies that it should be expressed in the inventory table just like all other emissions, in plain kg. (Often the amount will be specified in Bq instead of kg; in that case a conversion has to be made.) The nucleon number of the isotope may be included here, but the toxicity data are normally not different per isotope. Inclusion in the provisional toxicity method does not require that degradation data (i.e. half-life) is known. When the fate is to be included, as in the intended method, degradation data - whether due to chemical or to nuclear mechanisms - are required.

The interesting additional thing is the characterization of internal exposure to radiation. A possibility could be to use the annual limit of intake (ALI; Anonymous, 1979-1982) in a similar way as the air quality guideline (AQG) was used above (Heijungs *et al.*, 1992). This is again a critical volumes approach, with the remark that it is not about normal volumes in m^3, but about generalized volumes in year·kg body weight. For the provisional method, as long as degradation is not included, the equation reads:

$$R_{\text{internal}} = \sum_i \frac{m_i}{ALI_i} \tag{8}$$

and when fate is included one uses a form like:

$$R_{\text{internal}} = \sum_i \frac{K_i}{K_{ref}} \times \frac{ALI_{ref}}{ALI_i} \times m_i \tag{9}$$

where K_i measures somehow the exposure to radiation in a similar way as it is done in multi-media models, and *ref* represents some reference isotope, e.g. U^{238}. As in chemical degradation (Heijungs & Guinée, 1994), the proportionality factor will probably be inversely proportional to the half-life (τ).

An interesting problem in the field of radiation is the existence of decay series. After degradation, the resulting substance is mostly not harmless. Except for being toxic, it can decay once more, under the emission of other types of radiation with different energies. In principle, the full decay series could be taken into account. There is one reason to not include the decay series: equal treatment. In the intended method for human toxicity, an emission of e.g. DDT is assessed, taking into account the inherent toxicity and the half-life of DDT, but not taking into account the fact that it is degraded into another harmful substance (DDE). But one could argue with more reason that it is the other way round: that decay products of non-radioactive toxic substances should be taken into account, just like the decay products of radioactive substances.

External exposure to radiation

When radioactive substances are used within an economic process, they are normally not emitted. But the radiation itself can be emitted to the environment. This is also possible in economic processes where radiation is generated without the use of radioactive substances. Roentgen diagnosis and particle colliders are two examples. Furthermore, emissions of radioactive substances not only contribute to internal radiation, but to external radiation as well.

To be able to characterize the impacts of emissions of radiation, it is important to know what to include in the inventory table. Of course, the kind of radiation is important: alpha particles, gamma radiation, etc. Another aspect is the kinetic energy of these particles. A third aspect is the amount of radiation emitted, in relation to the operating time of the process.

These considerations could lead to an inventory table which list the following items:

- amount in Bq;
- characteristic energy in eV;
- type of particle (α, β^+, β^-, γ, n).

A more intensive study of the impact assessment may lead to additional data requirements, such as polarization. The first two items could be combined in one parameter for the total emitted energy.

The usefulness of this depends, however, on the way the impact assessment works.

One possible characterization could be to aggregate the radiated energy linearly, only correcting for the effectiveness of the radiation due to differences in equivalent dose, and adding the radiation associated with external exposure to emitted isotopes:

$$R_{\text{external}} = \sum_i Q_i \times \rho_i \times E_i + R_{\text{external, emissions}} \qquad (10)$$

where E_i is the energy of the ith type of decay, ρ_i is the amount radiated, and Q_i is 1 for β and γ, 0.1 for n and 0.05 for α. Of course this has some severe limitations:

- the exposure in the sense of the relationship between radiation and absorbed dose is not included;
- the linear additivity of low and high energies is not very realistic.

It is clear that these ideas need a profound study.

Discussion

It has been argued that studying the environmental consequences of alternative systems providing the same function requires an approach that avoids problem shifting by being twofold integrative:

- it should cover all life cycle stages;
- it should cover all environmental impacts.

With respect to the former, there remain some problems, e.g. on the emissions of landfilling, and on the inclusion of calamities, but the work that is being done in this inventory analysis related field is nearing completion.

The situation for the latter is somewhat more awkward: there is a large amount of consensus on the list of problems to be included, but generally accepted methods exist only for a few impact categories. For other impact types, consensus seems to be possible. As an indication of the problems to be solved, the following list suffices:

- global warming: what is the time horizon T, and how should substances that contribute indirectly to global warming be dealt with?
- acidification: how should differences in soil type and ecosystem sensitivity be dealt with?
- human toxicity: can we ignore background concentrations, synergism and antagonism, metabolites, and can we aggregate carcinogenic and allergic effects?
- radiation: do we need two separate impact categories, can we include decay series, and can we ignore shielding?

Many problems are by now being discussed in relevant scientific fora: IPCC, for instance, is working on the global warming models, and the LCA community within SETAC is discussing how to apply their results. For toxicity, we are in the fortunate position to have the Dutch RIVM doing excellent work in the context of risk assessment for chemicals in the environment, work which can, with some adaptations, be applied for use in LCA. Soon, a project to define equivalency factors for human toxicity and ecotoxicity will be undertaken jointly by RIVM and CML. We would like to take the opportunity to emphasize the possibilities IAEA has to initiate and stimulate the development of an environmental impact indicator for radiation, with equivalency factors for the use in LCA. After all, as LCA is the only tool to compare energy sources on an integrative way, we have to face the problem of the absence of an indicator of a very relevant problem: that of radiation.

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