Regional LCA in a global perspective

Wegener Sleeswijk, A.

Citation

Wegener Sleeswijk, A. (2010, September 2). *Regional LCA in a global perspective*. Uitgeverij BOX Press, Oisterwijk. Retrieved from https://hdl.handle.net/1887/15921

2

General prevention and risk minimization in LCA: a combined approach*

Abstract

Methods for life cycle assessment of products (LCA) are most often based on the general prevention principle, as opposed to the risk minimization principle. Here, the desirability and feasibility of a combined approach are discussed, along with the conditions for elaboration in the framework of LCA methodology, and the consequences for LCA practice. A combined approach provides a separate assessment of above and below threshold pollution, offering the possibility to combat above threshold impacts with priority. Spatial differentiation in fate, exposure, and effect modelling is identified to play a central role in the implementation. The collection of region-specific data turns out to be the most elaborate requirement for the implementation in both methodology and practice. A methodological framework for the construction of characterisation factors is provided. Along with spatial differentiation of existing parameters, two newly introduced spatial parameters play a key role: the sensitivity factor and the threshold factor. The practicability of the proposed procedure is illustrated by an example of its application. Providing a reasonable data availability, the development of separate LCA characterisation factors for the respective assessment of pollution levels above and below environmental threshold values seems to be a feasible task that may add to LCA credibility.

Keywords

above threshold values, below threshold values, effects, exposure, fate, general prevention, LCA, life cycle assessment (LCA), multimedia models, risk minimization, spatial differentiation, threshold values

---

* This chapter has been published as: Wegener Sleeswijk A (2001) General prevention and risk minimization in LCA: a combined approach. *Environmental Science & Pollution Research* **8**: 1-9.

2.1 Introduction

The question whether the emission-related environmental assessment of products using *life cycle assessment* (LCA) should be based on pollution levels (*general prevention*; 'less is better') or on expected effects (*risk minimization*; 'only above threshold') has been discussed since years. The question whether it is possible to combine both approaches in a practical sense, however, has hardly been addressed. In this chapter, a methodological framework for such a combined approach is proposed.

According to the original document in which the terms 'less is better' and 'only above threshold' were introduced (White *et al.* 1995) the 'only above threshold' approach is not compatible with the functional unit concept, and therefore not applicable in LCA. This statement has been outdated by the application of this principle in practicable LCA methodologies for the assessment of above threshold impacts (*cf.* Hogan *et al.* 1996, Potting *et al.* 1998).

(Barnthouse *et al.* 1997) distinguish two extreme principles with respect to the question of what should be the basis of the assessment of environmental harm. With respect to emissions, these extreme principles are described with the terms *general prevention* and *risk minimization*. While general prevention is considered as the principle behind the 'less is better' approach, risk minimization seems to be the driving force behind 'only above threshold' methods. In our view, it is very well possible to combine general prevention with risk minimization. In other words: the 'less is better' approach can very well be combined with a prioritisation of 'above threshold' impacts.

A combination of both principles could not only enrich existing LCA methodology, but may also be interesting in the context of other environmental assessment methods, especially where these methods have largely focussed on above threshold effects until now.

As Potting *et al.* (1999) pointed out already, the procedure is extremely simple in theory: for each chemical and each impact category, areas where the environmental threshold is exceeded should be kept apart from areas where this is not the case. Concentrations of a chemical in both types of areas should be assessed separately. Despite the simplicity of the procedure, its practical elaboration is not as easy as it may seem.

The goal of this chapter is threefold:

1. Discussing the desirability and feasibility of combining the principles of general prevention ('less is better') and risk minimization ('only above threshold') in LCA.
2. Elaborating the underlying reasons for the above-mentioned discrepancy between theoretical simplicity and practical complexity of combining these principles.

3. Proposing a generally applicable methodological framework for the separate assessment of above- and below-threshold pollution in LCA.

The following three sections pertain, respectively, to each of these goals. Simultaneously, the first two of these sections serve as a theoretical background for the third one.

2.2 Risk minimization and general prevention in the context of LCA

2.2.1 Background information

Two LCA concepts play a central role in this chapter: the *functional unit* and the *characterisation factor*. The *functional unit* is the assessment basis in LCA. To compare product alternatives which differ in lifetime and functional capacity, products are assessed on a functional basis, *e.g.* '1000 tonnes of cargo transport over 1000 kilometres' for the comparative assessment of different types of trucks.

The *characterisation factor* represents the relative potential harmfulness of a standard amount (*e.g.* 1 kg) of a chemical in the context of a certain impact category, compared to other chemicals. It is based not only on effect information (*e.g.* relative toxicity), but also fate (*e.g.* degradability) and exposure related information (*e.g.* uptake by crops). Fate, exposure and effect can be represented by separate, composing factors. Multiplication of an emission in the product life cycle with the corresponding characterisation factor delivers a quantitative effect score: the *category indicator result* (ISO 2000). Category indicator results of different chemicals can be summed over the impact category to which they belong.

Spatial differentiation has an influence on the number of characterisation factors, since the area where a chemical is emitted matters for the magnitude of its eventual effect: every area has its own characterisation factors. Since results can eventually be summed, however, spatial differentiation does not necessarily influence the number of category indicator results.

2.2.2 Risk and LCA

Usage of the term 'risk minimization' in the context of LCA suggests that LCA can be used for the assessment of risks. It may even suggest that LCA might be a special form of risk assessment. To a certain extent, this can perhaps be justified. Yet, it should be kept in mind that the risks, assessed with LCA, differ in nature from the risks that are usually assessed with (other forms of) risk assessment (Udo de Haes and Owens 1998). This difference is caused by the nature of the functional unit.

An important quality of emissions, caused by the life cycle of a product, is the fact that they are delimited in terms of time: they are only emitted during the time that they support the production or use of one functional unit – not a continuous production or use process. Consequently, their contribution to environmental concentrations – and therewith to environmental risks – is also delimited in terms of time (Heijungs and Guinée 1994). And even during this delimited time period, a functional unit will seldom be responsible for any environmental risk in its full extent. In the first place, many risks are caused by a number of different processes together. In the second place, many processes in a life cycle will not exist exclusively for the performance of the function, represented by the functional unit. Processes like electricity production support a great many product functions simultaneously. It is not easy to describe the direct relationships between the environmental risks, associated with such processes, and the functions supported. As a consequence, the category indicator results in LCA are inevitably rather abstract figures, that cannot be translated directly to easily imaginable or directly measurable environmental risks (Figure 2.1). Risk in LCA will always remain a rather abstract concept.

2.2.3 LCA and risk minimization

The most important difference between risk minimization and general prevention is the way in which pollution below certain environmental thresholds is treated. Below such thresholds, risks are generally considered to be negligible, or not observable. From the viewpoint of risk minimization, this pollution should be neglected, since its contribution to actual risk cannot be quantified, and is considered to be near to zero. The advantages of a separate assessment of 'above threshold' impacts in LCA are obvious: since these impacts are clearly more severe, they deserve prioritisation.

Spatial differentiation is thus an important requirement for the use of the risk minimization principle in LCA. The fact that this principle has hardly been applied until now is largely caused by inability, rather than by choice, since methods for handling spatial differentiation in LCA are not easily available.

2.2.4 LCA and general prevention

The general prevention principle is defined as the conviction that 'any perturbation in natural systems is likely to have some adverse effects and should be justified' (Barnthouse *et al.* 1997). In the context of LCA, this principle can be practically elaborated in its pure form for those emission-related impact categories for which concentrations below a certain threshold level are considered to cause no or no appreciable risk. Impact categories in this framework include *human toxicity*, *ecotoxicity*, *acidification*, and *eutrophication* (*cf.* Udo de Haes *et al.* 1999).

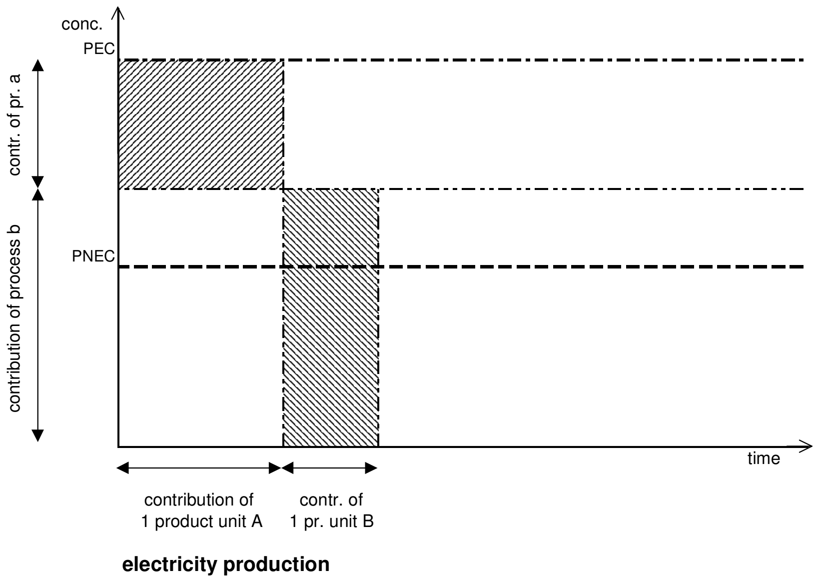

Figure 2.1 Contributions of products A and B to the environmental presence of a chemical emitted by an electric power station in terms of concentration (vertical axis) and time (horizontal axis). While B contributes more in terms of concentration (caused by its production process b), A contributes more in terms of time (caused by its production time). Their contributions to time-integrated concentrations (shaded) are almost equal.

The fact that in LCA the general prevention principle can only be applied in the context of impact categories is an important feature. It implies that it is possible that two different principles apply to one and the same environmental amount of chemical, in the context of two different impact categories to which this chemical potentially adds. For instance, sulphur dioxide is a substance that is considered hazardous in the framework of both acidification and human toxicity. Threshold values are not necessarily equal. It is therefore possible that for a certain environmental amount of sulphur dioxide, the risk minimization principle prevails in the context of *acidification*, while for *human toxicity*, the background concentration remains below the threshold, and the general prevention principle is the only principle that delivers a non-zero result.

2.2.5 The significance of general prevention

Barnthouse *et al.* (1997) mention two possible types of considerations behind the general prevention principle of 'knowledge limitations' and of 'religious/philosophical conviction'. From a scientific point of view, the first type is the most interesting one. Threshold values are usually concentrations below which effects are either not observed or considered negligible. It is commonly accepted that the fact that no effects are observed does not mean that effects do not occur at all, or will not occur in the future. This is especially important for those types of effects for which a care is felt for any effect, whether observed or not. The *human toxicity* impact category is probably the best example of a collection or such effect types: there is a common tendency to avoid unnecessary exposure to potentially hazardous chemicals, even in doses below the reference doses that are believed to be safe.

Knowledge limitations play an important role. More scientifically interesting types of considerations, however, may be distinguished. In the context of the LCA impact categories *ecotoxicity*, *eutrophication*, and *acidification*, at least three additional types may be considered. First, care may be felt when environmental effects are not yet manifest, but are believed to be imminent, *e.g.* when environmental buffers tend to be filled up. Second, a potentially eutrophying substance may occur in relatively high concentrations without causing any effect when it is not the limiting factor. Third, there is a fairly common conviction that it is undesirable that potentially ecotoxic chemicals should occur in the environment in concentrations that exceed natural background levels. In each of these situations, it will probably be commonly accepted that general prevention is useful.

What remains are concentrations of ecotoxics in amounts that do not cause natural background levels to be exceeded (*e.g.* small-scale emissions of heavy metals to the sea), and concentrations of potentially acidifying or eutrophying substances in insensitive areas. In our opinion, these emissions do not need to be assessed at all in LCA, not even in the context of general prevention.

A complicating factor in the application of the general prevention principle is the fact that the optimal environmental concentration of naturally occurring, potentially hazardous substances does not always equal zero. When background levels are below these optimal levels, anthropogenic emissions may be beneficial. Examples are emissions of potentially eutrophying substances to desert areas, and emissions of minerals (*e.g.* zinc, copper) in areas where concentrations of these minerals are sub-optimal for human health. Such emissions should not be assessed as hazardous in the context of the corresponding impact categories, and might even get a positive assessment.

2.2.6 The boundary between general prevention and risk minimization

In some cases, it will be hard to say which of the principles of general prevention and risk minimization applies. This may specifically occur in highly anthropogenic areas, where the prevailing circumstances largely deviate from the natural situation. In such areas, it can be difficult to establish threshold values. A severely polluted river – for instance – may be virtually lifeless. Natural ecosystems have disappeared. Additional effects are hardly possible. In such cases, it is not easy to establish an objective, scientific method to determine the threshold value. Should an emission to this river be considered to cause no risk? Or should the 'natural' threshold value of the river, as it was before pollution started, be applied?

Personally, I think the best solution in such situations is to take the prevailing circumstances as a starting point. After all, it does make a difference whether a chemical is emitted to an already heavily polluted area or to one of the few remaining pieces of unspoilt nature. The fact that we tend to prefer the protection of these virgin areas should be reflected in the assessment, that is, in the category indicator. This implies that threshold values in already polluted areas will have to be considered to be relatively high. This pragmatic solution should not be interpreted as a denial of the importance of combating existing pollution. In polluted areas, these artificial threshold values are just a device that has no meaning outside the context of LCA.

2.3 Combining general prevention with risk minimization

2.3.1 Starting basis

In the former section, the principles of general prevention and risk minimization have been discussed separately. In this section, it will be shown how these principles can be combined. The core of the approach is that pollution levels in above and below threshold areas are kept apart from each other, and are assessed separately. It has been mentioned already that spatial differentiation is a requirement for this approach. The bottleneck for the development of generally applicable methods for spatial differentiation is the enormous amount of information they require. Since product life cycles as a whole will seldom be limited to a particular part of the world, spatial information on fate, exposure and effect characteristics should preferably have a global coverage. The implications for each of these three fields, and the practical consequences for LCA methodology as a whole, are discussed in this section.

2.3.2 Fate modelling

In order to cover all impact categories on a global scale, LCA needs a worldwide multimedia fate model. The most convenient candidates are probably the Mackay type multimedia box models (Mackay 1991). These models account for degradation, immobilisation, intermedia transport, and transport within one medium between different boxes. They are often used for large-scale screening purposes in the context of risk assessment. Two main model variants can be distinguished: the steady state variant ('level 3') and the dynamic variant ('level 4'). In principle, the dynamic variant would be the most appropriate to handle the non-continuous type of emissions that are typical for LCA. The outcome of such models is a concentration course for each environmental compartment. Environmental concentrations can thus be determined at any point of time. What we need in LCA, however, is the time- and space integrated value of the entire concentration curve. Deriving this value would require some modest model adaptations. But a simpler solution is also available. It can be proven that the outcome of the time integration mentioned is numerically identical to the steady-state concentration, caused by an emission flux (kg/year) that is numerically identical to the emission pulse (kg) to be evaluated (Heijungs 1995). Since mixing is assumed to be homogeneous, integration over space can be performed by simply multiplying this value with the magnitude of the distribution volume. Thus, steady state modelling can be used as an expedient for the calculation of the time-integrated environmental amounts (kg·s) that form the assessment basis for emissions in LCA. This is already common practice (*cf.* Guinée *et al.* 1996, Huijbregts *et al.* 2000). In order to keep it clear that the results of the operation should not be interpreted as steady-state concentrations, I would suggest to adapt some terms, to replace *PEC* (predicted environmental concentration) by *PEA* (predicted environmental amount), or *EEC* (expected environmental concentration) by *EEA* (expected environmental amount).

For proper fate modelling, spatial differentiation is a condition, since variables such as temperature, rainfall, wind speed, and ratios between land and water coverage play a central role in multimedia models. In its turn, a spatially differentiated fate model is a condition for making an adequate distinction between above and below threshold exposure, since many chemicals are easily transported from the original emission location to other areas.

2.3.3 Exposure modelling

For water and soil ecosystems, concentration and exposure are sometimes almost used as synonyms. For species for which the direct exposure to the medium in which they dwell is the dominant exposure route, concentration and exposure will indeed be more or less proportional, at least per environmental volume unit. For the assessment of environmental impact on human health, however, additional exposure modelling is indispensable. Inhalation of contaminated air and ingestion of contaminated food are probably the most important routes for human exposure. The spatial aspect is important with respect to regional differences in food consumption patterns, and – above all – with respect to the enormous differences in population densities that exist on a global scale.

2.3.4 Effect modelling

Effect parameters differ per chemical and per impact category. They serve three different purposes:

- to distinguish between sensitive and insensitive areas
- to distinguish between above and below threshold areas
- to establish the relative harmfulness of substances compared to each other.

It is difficult to determine which parameters are the best indicators for the harmfulness of a substance in a general sense, that is, independent of its background concentration. Currently, the most widely used parameters are probably the *no observed effect concentration* (NOEC) for ecotoxicity and the *acceptable daily intake* (ADI) for human toxicity assessment. Regarding the large uncertainties that are associated with the NOEC (*cf.* Chapman *et al.* 1996), it can be considered whether EC_{50} values could serve as a more confident assessment basis for ecotoxicity. With respect to human toxicity, an expert panel has recommended the use of direct toxicity measures, rather than ADI values or similar safety limits (ILSI 1996).

2.3.5 Practical consequences

The necessity of a comprehensive spatial differentiation is probably the most important reason why a general method for the separate assessment of above and below threshold pollution in LCA is not yet available. The construction of such a method would require a vast amount of data. The differentiation level should be low enough to keep a global multimedia model manageable, but high enough to make sense in the context of reliability.

A methodological consequence of spatial differentiation is the necessity to collect fate, exposure and effect parameters on the required level. On the basis of fate and exposure parameters, a global fate and exposure model should be constructed. The effect parameters could be added in separate effect modules for the different impact categories. With the fate and exposure model, it will be possible to produce the time-integrated environmental amounts in every area for all environmental compartments, as well as the time-integrated human exposure in every area, caused by a standard emission of a chemical. With the effect module, it will be possible to distinguish between exposure amounts in sensitive and non-sensitive areas and in above and below threshold areas, respectively, and to weight the severity of standard emissions of different chemicals against each other, for every separate impact category. The result will be an extensive list of characterisation factors for all emission areas distinguished.

Probably one of the most convenient levels to locate processes in LCA is the level of individual countries and oceans. For modelling parameters, this is also a level at which a lot of information is generally available. A disadvantage of the use of countries and oceans as a basic level for spatial differentiation is their incongruity and freakishness. For large countries and oceans, the assumption of homogeneity with respect to concentrations, landscape, climate and population density will be far beside reality. It may be necessary to split up these countries and oceans.

One of the constraints on the applicability of spatial differentiation is the fact that the exact locations of emissions in LCA are often unknown, or even indeterminate. Indeterminacy occurs when the research question is of a general character, *e.g.* 'What is environmentally preferable: paper or plastic wrappings?' Sometimes, it occurs for single processes within a product life cycle, *e.g.* when required aluminium is bought on the world market. In such cases, the best solution is probably to use a probabilistic approach for locating industrial processes artificially, rather than working with global average values for fate, exposure and effect parameters.

Apart from the methodological level, spatial differentiation has also consequences on the level of application. In the LCA *inventory analysis*, it will not be sufficient to collect unit process emission data as such: all emission data should be specified with respect to location on the required level (*e.g.* countries and oceans). This implies that existing LCA databases that lack such information can no longer be used as such. Moreover, the magnitude of the inventory table will be manifold, since different emissions of the same chemical to the same environmental medium can no longer be summed, unless they are emitted in the same area. In the LCA *impact assessment*, all these separate emissions have to be multiplied by the corresponding characterisation factor. The eventual result, however, will be comparable in size and transparency with the existing situation. Instead of one *category indicator result* per impact category, there will be two for some impact categories: one for above, and one for below threshold pollution.

2.4 A methodological framework

2.4.1 Procedure

A basic requirement for the application of the theory sketched in the former sections is an automated, spatially differentiated, flexible fate and exposure model that accounts for environmental transport between different areas in both directions for every environmental medium, and for direct and indirect human exposure via these media. Based on theory discussed in the former sections, separate above and below threshold LCA characterisation factors can be calculated with such by the application of a nine-step procedure.

According to Heijungs and Wegener Sleeswijk (1999), LCA characterisation factors are composed of three separate constituting factors: the fate, exposure and effect factor, respectively. Spatial differentiation refers to each of these constituting factors. When both the fraction of area that is sensitive in the context of each impact category and the fraction of area where the environmental threshold is exceeded are taken into account, this results in two extra factors: the sensitivity factor and the threshold factor. The sensitivity factor indicates the fraction of area that is sensitive to a certain impact category, *e.g.* the fraction of area covered by acidification- sensitive ecosystem, while the threshold factor indicates the fraction of sensitive area where a threshold (*e.g.* the *critical load* for acidification) is exceeded.

In the procedure described below, the resulting five factors will be worked out separately before being combined into two overall characterisation factors for above and below threshold situations, respectively.

1. Collect substance data as required by the model used
Substance data cover physicochemical properties, half-life times in different media, and bio-concentration factors. The exact data required may slightly differ per model, depending on the level of detail covered.

2. Divide up the world into a number of areas, on the basis of differences with respect to fate, collect the area-specific parameters required by the fate and exposure model, and introduce the areas with the corresponding parameters into the fate and exposure model
Since fate is the only aspect that covers all emission-related impact categories, it is the most convenient basis for the distinction between different areas. Differences in fate per area may be caused by climatological or geographical differences. The total number of compartments to be distinguished depends on the level of detail intended. For fate modelling, it is necessary to distinguish at least a number of different climate zones. Since the ratio between land and water coverage can have an important influence the fate of a chemical, it may be desirable to distinguish on this basis between a number of different geographic areas as well. For human exposure modelling, it is important to distinguish between areas that differ with respect to population density. Differences in consumption patterns are another influencing factor.

3. Evaluate the fate factors: calculate the relative distribution of every substance over all environmental compartments, for a standard emission to each of the emission compartments, and multiply the resulting time-integrated concentrations by the corresponding compartmental volumes.
Application of the spatially differentiated multimedia fate model to a standard emission amount of 1 kilogram yields a number of time-integrated concentrations (in $kg \cdot m^{-3} \cdot kg^{-1} \cdot s$): one for each compartment to which an emission can be transported from it either directly or indirectly from the original emission compartment. Multiplication of these values with the volumes of the corresponding compartments delivers the LCA fate factors (in s).

4. Evaluate the exposure factors: calculate the 'standard' exposure to each compartment by multiplying the population magnitude in every area by the corresponding average individual exposure magnitude (based on inhalation and food consumption) for each separate compartment, for a standard time-integrated amount of substance present in that compartment
Contrary to fate factors, exposure factors are more or less impact category specific. Commonly, exposure as such is only taken into account for the impact category 'human toxicity'. It is determined by the direct and indirect exposure to different environmental compartments – largely via inhalation and food and drinking water consumption – and by population magnitude.

Reference doses for human exposure are often expressed per kilogram body weight. In order to combine these values with population magnitudes, it is necessary to convert these doses to doses per individual.

5. Evaluate the sensitivity factors: the fraction of each area that is considered to be sensitive to every separate impact category

6. Evaluate the threshold factors: the fraction of each sensitive part of an area in which the threshold is exceeded, and the fraction in which it is not exceeded, for each individual substance in the context of every separate impact category

7. Determine for each area the effect parameters: an average relative effect measure for each individual substance in the context of every separate impact category, for every exposure route

These parameters aim to set values to determine the relative harmfulness of different substances, in proportion to each other, in the context of every separate impact category. Effect parameters should not include any fate or exposure-related aspects.

8. Evaluate the effect factors: calculate a measure for the average expected effect within each compartment (or: caused by exposure to this compartment) for every impact category

Effect factors should be proportional to the expected effect. Sometimes, inverse effect measures can be used directly as effect factors. Effect measures for different compartments should, however, be expressed in the same dimension for the same impact category. For the human toxicity impact category, this implies that air quality measures in terms of concentrations should be converted to doses, in order to make the effect factors for air, water, and soil mutually compatible. Moreover, effect factors should be compatible with the corresponding exposure factors. For human toxicity, this implies that doses per kilogram bodyweight should be converted to doses per individual. When the average body weight per country is assumed to differ per country, this is an extra source of spatial differentiation.

9. Evaluate the characterisation factors: multiply fate factor, exposure factor, sensitivity factor, threshold factor, and effect factor and aggregate the resulting exposure factors per substance and per impact category for above and below threshold situations by summation

In formula:

$$Q_i^{jn} = \sum_m F_i^{nm} \times X_i^{mj} \times S^{mj} \times T_i^{mj} \times E_i^{mj}$$

where

Q_i^{jn} = characterisation factor for substance *i* in impact category *j*

F_i^{nm} = fate factor that accounts for transport of substance *i* from compartment *n* to compartment *m* and for degradation in compartment *n*

X_i^{mj} = exposure factor that accounts for the average exposure to substance *i* from compartment *m* by the target, corresponding to impact category *j*

S^{mj} = sensitivity factor that accounts for the fraction of compartment *m* that is sensitive for impact category *j*

T_i^{mj} = threshold factor that accounts for the fraction of compartment *m* in which the environmental threshold is either exceeded (for above-threshold calculations) or not exceeded (for below threshold calculations)

E_i^{mj} = effect factor that accounts for the average environmental sensitivity in compartment *m* with respect to impact category *j* for the exposure to substance *i*.

The resulting characterisation factors are part of the LCA method. These factors can be applied in individual case studies by the multiplication of every emission in the product life cycle with the corresponding characterisation factor. The resulting category indicator results are summed per impact category for above and below-threshold situations. Together, these summed category indicator results from the environmental profile of the product under study.

2.4.2 Exemplification

The author of this chapter is currently working on a global fate and exposure model called GLOBOX that meets the requirements mentioned in the former subsection. The model will be spatially differentiated on the level of separate countries and oceans. Since it is not yet operational, it is not possible to calculate fate and exposure factors with it. The fate and exposure factors for this example could therefore not yet be calculated, and have been left out. The same applies to the characterisation factors. Other area-related parameters should be considered as preliminary values that may be changed in the final model.

With respect to environmental transport and degradation equations, the GLOBOX model is largely based on the Dutch model USES 2.0. The parameter requirements of this last model will be used as a basis in this example. The example refers to three emissions: an emission of sulphur dioxide (SO_2) to air, an emission of toluene to water, and an emission of pentachlorophenol (PCP) to soil. These emissions are evaluated in the context of two impact categories: *human toxicity* and *acidification*. The world is divided into countries and oceans. The example is limited to two countries: Norway and Sweden. Only spatially differentiated parameters are mentioned in the table. For the other parameters, default values are assumed to be included in the model. The goal of this example is to give an overview of the parameters to be collected in practice (see Step 1-9):

Step 1: Substance parameters

parameters	sulphur dioxide	toluene	PCP
molecular weight [g·mole^{-1}]	64.07	92.13	266.4
melting point [K]	200	178	462
vapour pressure [Pa]	3.3E+5	2.93E+3	0.013
log K_{ow}	–	2.79	4.8
water solubility [g·m^{-3}]	1.16E+5	5.15E+02	0.14
half-life for photodegradation in air [h]	16.8	31	–
half-life for biodegradation in freshwater [h]	–	120	24
half-life for biodegradation in soil	–	27	1080

Step 2: Areas for spatial differentiation, with the corresponding fate and exposure parameters

areas for spatial differentiation	Norway	Sweden
area [km^2]	324,220	449,964
fraction of area covered by water [–]	0.05	0.09
fraction of area covered by agricultural soil [–]	0.03	0.08
population [individuals]	4,481,162	8,873,052
intake of freshwater fish [$\mathrm{g \cdot ind.^{-1} \cdot d^{-1}}$]	10	3
intake of marine fish [$\mathrm{g \cdot ind.^{-1} \cdot d^{-1}}$]	40	22
intake of leaf crops [$\mathrm{g \cdot ind.^{-1} \cdot d^{-1}}$]	512	481
intake of root crops [$\mathrm{g \cdot ind.^{-1} \cdot d^{-1}}$]	125	100
intake of meat [$\mathrm{g \cdot ind.^{-1} \cdot d^{-1}}$]	87	68
intake of dairy [$\mathrm{g \cdot ind.^{-1} \cdot d^{-1}}$]	615	747

Step 3: Fate factors

distribution compartment	fate factor for emission of substance (…) to emission compartment (…)					
	SO_2 air Norway	toluene fresh w. Norway	PCP agr. soil Norway	SO_2 air Sweden	toluene fresh w. Sweden	PCP agr. soil Sweden
air Norway	…	…	…	…	…	…
freshwater Norway	…	…	…	…	…	…
agr. soil Norway	…	…	…	…	…	…
air Sweden	…	…	…	…	…	…
freshwater Sweden	…	…	…	…	…	…
agr. soil Sweden	…	…	…	…	…	…

Step 4: Exposure factors

human exposure factor of substance (…) to emission compartment (…)					
SO_2 air Norway	toluene fresh w. Norway	PCP agr. soil Norway	SO_2 air. Sweden	toluene fresh w. Sweden	PCP agr. soil Sweden
…	…	…	…	…	…

Step 5: Sensitivity factors

fraction of area that is sensitive to acidification	
Norway	Sweden
0.683	0.862

Step 6: Threshold factors

impact categories	fraction of sensitive area where threshold is exceeded					
	Norway			Sweden		
	SO_2	toluene	PCP	SO_2	toluene	PCP
human toxicity	0	0	0	0	0	0
acidification	0.26	–	–	0.15	–	–

Step 7: Effect parameters

human toxicity	effect measure human toxicity		
	SO_2	toluene	PCP
threshold value for inhalation [$\mu g \cdot m^3$]	50	3000	–
threshold value for ingestion [$\mu g \cdot kg$ b.w.$^{-1} \cdot d^{-1}$]	–	430	30

acidification	effect measure acidification		
	SO_2	toluene	PCP
acidifying potential [kg SO_2 -equivalents]	1.0	–	–

Step 8: Effect factors

human toxicity	effect factors human toxicity		
	SO_2	toluene	PCP
oral exposure [$s \cdot kg^{-1}$]	–	2.3E+9	4.1E+10
inhalatory exposure [$s \cdot kg^{-1}$]	8.6E+10	2.3E+9	4.1E+10

acidification	effect factors acidification		
	SO_2	toluene	PCP
air distribution [kg SO_2 -equivalents]	1	–	–

Step 9: Characterisation factors

emission compartment	characterisation factor for impact category (…) of substance (…)			
	human toxicity			acidification
	SO_2	toluene	PCP	SO_2
air Norway	…	…	…	…
freshwater Norway	…	…	…	…
agr. soil Norway	…	…	…	…
other soil Norway	…	…	…	…
air Sweden	…	…	…	…
freshwater Sweden	…	…	…	…
agr. soil Sweden	…	…	…	…
other soil Sweden	…	…	…	…

2.5 Conclusion

Above and below-threshold pollution are both important environmental issues that are worth being taken into account in LCA. Preferably, however, they should be assessed separately. Above-threshold pollution is directly connected to risk, and should therefore be combated with priority.

Spatial differentiation is a condition for the distinction of above and below-threshold conditions. Because of the global character of LCA, and the indeterminacy of exact unit process locations that is typical of LCA, the level of spatial resolution cannot be too high. Differentiation on the level of individual countries is probably the most convenient option.

The choice for a separate assessment of above and below-threshold pollution in LCA will have consequences for both methodology and practice. The recommended methodological adaptations require that existing fate, exposure, and effect parameters are replaced by spatially differentiated parameters. Effect parameters should include two new elements: the sensitivity factor and the threshold factor. For LCA practice, consequences are largely limited to the need to collect spatially-differentiated emission data.

It has been shown that separate assessment of above and below-threshold pollution in LCA is theoretically feasible. Practical feasibility depends on data availability, but does not seem to be fully out of the question. A methodological implementation of the proposed procedure will bring LCA nearer to risk assessment, without losing track of the specific characteristics of life cycle impact assessment.

Acknowledgement

The author would like to thank Helias A. Udo de Haes for his valuable comments. The author is grateful to Unilever for financing her PhD project, in the context of which this chapter has been written.

References

Barnthouse L, Fava J , Humphreys K, Hunt R, Laibson L, Noesen S, Owens J, Todd J, Vigon B, Weitz K, Young J (eds.) (1997) *Life-Cycle Impact Assessment: The State-of-the-Art.* SETAC, Pensacola, Florida, USA

Chapman PM, Caldwell RS, Chapman PF (1996) Warning: NOECs are Inappropriate for Regulatory Use. Letter to the Editor. *Environ Toxicol Chem* **15**: 77-79

Guinée J, Heijungs R, Van Oers L, Wegener Sleeswijk A, Van de Meent D, Vermeire T, Rikken M (1996) USES, Uniform System for the Evaluation of Substances. Inclusion of Fate in LCA Characterisation of Toxic Releases Applying USES 1.0. *Int J LCA* **1**: 133-138

Heijungs R (1995) Harmonization of Methods for Impact Assessment. *Environ Sci Pollut Res* **2**: 217-224

Heijungs R, Guinée JB (1994) The Flux-Pulse Problem in LCA. *LCA News* **4**: 6-7

Huijbregts MAJ, Thissen UMJ, Guinée JB, Jager T, Kalf D, Van de Meent D, Ragas AMJ, Wegener Sleeswijk A, Reijnders L (2000) Priority Assessment of Toxic Substances in Life Cycle Assessment. Part I: Calculation of Toxicity Potentials for 181 Substances with the Nested Multi-Media Fate, Exposure and Effects Model USES-LCA. *Chemosphere* **41**: 541-573

ILSI (1996) *Human Health Impact Assessment in Life Cycle Assessment: Analysis by an Expert Panel.* ILSI Health and Environmental Science Institute, Washington DC, USA

ISO (2000) *Environmental Management – Life Cycle Assessment – Life Cycle Impact Assessment. ISO/FDIS 14042:(E).* First edition 2000-03-01. ISO 14042: 2000, Geneva, Switzerland

Mackay D (1991) *Multimedia Environmental Models. The Fugacity Approach.* Lewis Publishers, Chelsea, Michigan, USA

Potting J, Hauschild M, Wenzel H (1999) "Less is Better" and "Only Above Threshold": Two Incompatible Paradigms for Human Toxicity in Life Cycle Assessment? *Int J LCA* **4**: 16-24

Potting J, Schöpp, W, Blok K, Hauschild M (1998) Site-Dependent Life-Cycle Impact Assessment of Acidification. *J Ind Ecol* **2**: 63-87

Udo de Haes HA, Jolliet O, Finnveden G, Hauschild M, Krewitt W, Mueller-Wenk R (1999) Best Available Practice Regarding Impact Categories and Category Indicators in Life Cycle Impact Assessment. Background Document for the Second Working Group on Life Cycle Impact Assessment of SETAC-Europe (WIA-2). *Int J LCA* **4**: 66-74 and 167-174

Udo de Haes HA, Owens JW (1998) *Evolution and Development of the Conceptual Framework and Methodology of Life-Cycle Impact Assessment.* Society of Environmental Toxicology and Chemistry, Pensacola, Florida, USA

Wania F, Mackay D (1995) A Global Distribution Model for Persistent Organic Chemicals. *Sci Total Environ* **160/161**: 211-232

Wegener Sleeswijk A (1997) *Product versus Process in Impact Assessment.* Proceedings, Eco Informa'97, München, pp. 192-197

White P, De Smet BB, Udo de Haes HA, Heijungs R (1995) LCA Back on Track. But is it One Track or Two? *LCA News* **5**: 2-4