Regional LCA in a global perspective

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Similarities, differences and synergisms between HERA and LCA – an analysis at three levels*

Abstract

Linkages between Human and Environmental Risk Assessment (HERA) and Life Cycle Assessment (LCA) can be analysed at three levels: the basic equations to describe environmental behavior and dose-response relationships of chemicals; the overall model structure of these tools; and the applications of the tools. At level 1 few differences exist: both tools use essentially the same fate and effect models, including their coefficients and data. At level 2 distinctive differences emerge: regional or life cycle perspective, emission pulses or fluxes, scope of chemicals and types of impacts, use of characterisation factors, spatial and temporal detail, aggregation of effects, and the functional unit as basis of the assessment. Although the two tools typically differ in all these aspects, only the functional unit issue renders the tools fundamentally different, expressing itself also in some main characteristics of the modeling structure. This impedes full integration, which is underpinned in mathematical terms. At level 3 the aims of the tools are complementary: quantified risk estimates of chemicals for HERA versus quantified product assessment for LCA. Here, beneficial synergism is possible between the two tools, as illustrated by some cases. These also illustrate that where full integration is suggested, in practice this is not achieved, thus in fact supporting the conclusions.

Keywords

HERA, LCA, functional unit, toolbox, combined approach

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3.1 Introduction

Human and Environmental Risk Assessment (HERA) and Life Cycle Assessment (LCA) are often associated with each other. We observe that the comparison between the two types of tools in the course of the development of LCA has become increasingly accurate and detailed. At the same time still quite some 'wrestling' takes place with the topic. Where are the two types of tools the same, where do they differ, and which differences are fundamental?

Let us start with a short description of the two tools. HERA is seen here as a tool, analyzing the risks for human health and for the environment associated with the regular release of chemicals. In the Organization for Economic Co-operation and Development's (OECD 1995) framework, it consists of four steps: hazard identification, where the capacity of a chemical to cause adverse effects is investigated; exposure assessment, where the emission volume of and the degree of exposure to a chemical is determined; hazard assessment, where the dose-response relationship for the chemical is determined; and risk characterisation, in which the results of exposure assessment and effect assessment are compared to one another, often in the form of the ratio of the predicted environmental concentration (PEC) to the predicted no-effect concentration (PNEC). In contrast, LCA is a tool for the analysis of environmental impacts associated with products (including services) over their whole Life Cycle (*i.e.*, product systems); it consists of four main 'phases' (as called in the ISO 14040 series on LCA), that is: Goal and Scope Definition, Inventory Analysis, in which the processes composing a product system are analysed, Impact Assessment, in which the environmental impacts associated with these processes are analysed, and Interpretation, in which the results are compared with the goals set in the Goal and Scope Definition phase. It is the Life Cycle Impact Assessment phase (or LCIA), including impacts both on humans and on the environment, which bears resemblance with a large part of HERA; therefore this chapter will mainly focus on this phase of LCA. In particular, it is the characterisation step of LCIA where models and concepts akin to those of HERA are used to quantify the contributions of releases of chemicals in terms of impacts to humans and ecosystems.

In the first main reports on LCA in general and LCIA in particular, particularly from Heijungs *et al.* (1992), Fava *et al.* (1993), and Lindfors *et al.* (1995), no operational connection to HERA has been made; LCA largely stands by itself. The same holds true for the International Organization for Standardization (ISO) standards on LCA (ISO 1997, 2000). Any reference to risk assessment approaches is missing. A first implementation of the use of Risk Assessment models in LCIA is discussed by Guinée and Heijungs (1993), focusing on toxic impacts. Later, White *et al.* (1995) discuss the position of the tools in relation to each other in a more general sense, distinguishing between an 'only above threshold approach,' like in HERA, and a 'less-is-better-approach,' like particularly in LCA, using a functional unit as reference. In line with this, but much more precise, Barnthouse *et al.* (1997) distinguish between two types of techniques. They summarise the difference as follows: 'LCIA focuses on relative, marginal comparisons of systems using a functional unit approach'; and, in contrast: 'environmental ... risk assessment work(s) with absolute measures such as actual concentrations' (p. 5).

In this context the concept of the 'functional unit' in LCA needs clarification. LCA aims to compare different products 'from cradle-to-grave' (*i.e.*, product systems) with respect to their environmental impacts. Such a comparison only makes sense, if the two products do fulfill the same function, qualitatively and quantitatively. Thus, not one milk bottle and one milk carton should be compared, but for instance 40 bottles and 1,000 cartons, both capable of the packaging of 1,000 liters of milk. The latter is the functional unit. It is an arbitrarily chosen unit of function, aiming to achieve comparability between the product systems at stake. Other examples include: one square meter painted for a period of 10 years; or: one passenger transport between Amsterdam and London.

Owens (1997) proposes to use HERA as a more detailed and site-specific analysis after an LCA has been carried out; Assies (1998) goes one step further and offers a method to include background levels to incorporate elements of HERA into LCA. In Wrisberg *et al.* (2002), LCA and HERA are systematically compared on a much larger number of issues, including among others the relationship to a functional unit. Cowell *et al.* (2002) mention this as a core aspect in their comparison of LCA and HERA.

Recently, more in depth investigations have been carried out where the two types of tools are the same and where they do differ, again focusing on a broad number of issues. By doing so, Olsen *et al.* (2001) identify a number of harmonies and discrepancies between the two types of tools, focusing on Risk Characterisation of chemicals and Life Cycle Impact Characterisation of chemicals. They conclude that the relative character of LCA due to the use of the functional unit is a very important feature of LCA, in contrast to the absolute character of RA. They also conclude that there are overlaps between the tools and that they can complement each other in an overall environmental effort. Wegener Sleeswijk *et al.* (2003) go one step further and conclude that although LCIA and HERA are not fundamentally different on most investigated topics, the functional unit approach in LCA remains as a central, fundamentally different point of distinction. Interestingly enough, the authors still make a plea for integration of both tools. This plea for integration of the two tools is more explicitly the aim of a recent study by the Swedish Environmental Protection Agency (Flemström *et al.* 2004).

In summary, the following picture arises. The two tools, HERA and LCIA, have much in common; they also differ in a number of aspects, the use or not-use of the functional unit being a, or even the main point of difference; the question to which extent the two tools can be integrated needs further investigation, together with the need for clarification about what in fact is meant by 'integration'; and in their application the two tools can complement each other.

In this chapter, we build on this arising picture. In order to achieve more clarity on the harmonies and discrepancies and on the potentials of 'integration' of the two tools, we will distinguish between three levels of analysis: (1) the level of the basic equations to describe the environmental behavior and dose-response relationships of chemicals as used in Risk Characterisation and in Life Cycle Impact Characterisation; (2) the level of the overall model structure of these analytical tools; and (3) the level of their applications. At all three levels, the focus will be on the impact of toxic substances, being the main focus of HERA, and therefore the main field of attention.

The first level, dealing with the basic equations on the fate and effect of chemicals, the inclusion in the two tools, will shortly be discussed. The second level, dealing with the overall modeling structure, will be investigated in more depth where the differences between HERA and LCIA are indeed fundamental in character. This will be achieved using both a conceptual approach, focusing on various characteristics, and a mathematical underpinning of the differences. And at the third level a number of case studies will be discussed of combined use in practice. As a result, a picture is to emerge as to what the common basis of Risk Characterisation and Life Cycle Impact Characterisation is, what the fundamental differences are, and where there can be beneficial synergism.

3.2 Level 1: basic equations

The first level of analysis concerns the basic ingredients of the tools. These are:

- the environmental processes and other phenomena that are to be incorporated (such as biodegradation of chemicals, infiltration in soil, ingestion of chemicals incorporated in food);
- the mathematical relationships postulated for each of these phenomena (such as the principle of mass conservation, the approximation of first-order kinetic chemistry, the lognormal approximation to the distribution of species sensitivity);
- the chemical and environmental data needed in these relationships (such as the octanol water partition coefficient, bio-concentration factors, the ambient temperature).

Both LCIA and HERA in principle use the same relationships and data from environmental chemistry, ecology, and human and eco-toxicology to model the behavior and impacts from chemicals released to the environment.

There may be some differences in practice, though. A specific HERA study is usually restricted to one single substance, whereas a specific LCA study deals with many hundreds of chemicals. Therefore, HERA can use more sophisticated models to cover more specialised phenomena. An example concerns the use of the biotic ligand model (BLM) (DiToro *et al.* 2001; Niyogi and Wood 2004), which may be used for HERA for copper and silver and a few other chemicals; in LCIA its usefulness is as yet limited, because it does not enable an equal approach for all chemicals to be included. Likewise, one HERA study is usually restricted to a particular site, but it can also extend to the level of a country or region; in contrast, a typical LCA study spans the entire globe. As a consequence, in HERA, more site-specific conditions can be handled than in LCIA. Thus, LCIA will in general cover fewer environmental processes, and the processes that are covered will in general be dealt with in a more simplified or generic way. Further, we can observe that HERA more often uses stochastic models and data than does LCA (Cooke and Bedford 2001). Nevertheless, HERA and LCIA use essentially the same chemical, toxicological and ecological processes, relationships, and data.

Another difference is that HERA will and should in general be used in a more conservative way than LCA. HERA often focuses on regulating the admission of chemicals in a safe way, thus requiring the use of safe levels and safety factors for less-known chemicals. As indicated in the introduction, LCA is not used for admission, but for comparison. This requires that most-realistic data are used instead of (realistic) worst-case values. In line with this, HERA typically focuses on fifth percentile values (like in HC_5, LD_5, or ED_5), whereas LCIA focuses on the 50-percentile values (HC_{50}, etc.) (*cf.* Payet and Jolliet 2005). Still, the same data sources are shared between LCIA and HERA.

These theoretical considerations on the similarities between LCIA and HERA are also reflected by the development of these tools in practice. For instance, important parts of the USES (Uniform System for the Evaluation of Substances) model for HERA (Jager and Visser 1994) has been used within LCIA by Guinée *et al.* (1996) and by Huijbregts *et al.* (2000), as the CalTox model for HERA (Maddalena *et al.* 1995) has been used in LCA by Hertwich *et al.* (2001). More recently, developments within the use of species-sensitivity distributions (SSDs) within HERA (Posthuma *et al.* 2002) have been taken up in LCA by Huijbregts *et al.* (2002) and Udo de Haes *et al.* (2002).

3.3 Level 2: overall model structure

3.3.1 Fundamental versus secondary differences

The second level of analysis concerns that of the overall model structure of the tools with respect to the general concepts applied and the mathematical framework. As this section deals with this overall model structure, HERA will not be compared with LCIA only, but also with LCA as a whole. The model structure of a tool reflects its function in two main respects: (1) main goal (2) scope.

Different overviews have been published to illuminate the similarities and differences between HERA and LCA in each of these respects (*cf.* Olsen *et al.* 2001; Udo de Haes *et al.* 2002; Sonnemann *et al.* 2004;Wegener Sleeswijk *et al.* 2003; Flemström *et al.* 2004; Pennington *et al.* 2004). As a general conclusion, we state that fundamental differences are related to the main goal of the tools, whereas scope and areas of application give rise to secondary differences of a more incidental character. In this section, we shall underpin this central statement by providing a stepwise description of the various differences (conceptual analysis). This description is underpinned in symbolic terms (mathematical analysis) presented in an annex to this chapter. Together these constitute a basis for the next section on combining both tools in practice.

3.3.2 Conceptual Analysis

According to Wegener Sleeswijk *et al.* (2003), the following main characteristics of LCIA can be identified as compared to HERA:

a. Life cycle perspective

b. Product as object of analysis

c. Number of processes, chemicals, and impact categories involved

d. Range of impacts covered

e. Use of characterisation factors

f. Summation of effects of different chemicals

g. Independence of time and location

h. Emission pulses instead of fluxes

i. Functional unit as a basis of assessment

And we add to this:

j. Relative and absolute character of the assessment

We will now discuss to what extent these differences are fundamental or only secondary.

a. Life cycle perspective

Despite the term 'life cycle assessment,' assessment from a life cycle perspective is not restricted to LCA. Application of the Life cycle perspective as such is sometimes defined as *life cycle thinking* (Fava 2002). Likewise, Life Cycle Management (or LCM) can build on more tools than LCA alone (*cf.* Wrisberg *et al.* 2002). The introduction of life cycle thinking in HERA implies that the purpose of risk management no longer remains restricted to one central process, but that upstream and downstream processes are accounted for as well, either in a qualitative or in a quantitative form. In this way, risk assessment can be performed in a life cycle framework. This is particularly clear from the EUSES (European Union System for the Evaluation of new and existing Substances) model, where risks are evaluated at every stage of a chemical's life cycle, and multiple sources of exposures to a single substance are considered (ECB 1997). This is implemented by calculating concentrations and exposures on an average basis for the entire region in which the different processes composing the life cycle take place. It can be concluded that not only for LCA, but also for HERA, an aggregation of releases across the life cycle may take place.

b. Product as object of analysis
In LCA, not chemicals as such, but products (including services) – as the cause of the emission of chemicals – form the object of the analysis; or more precisely, product systems, that is, all processes related to a product in its full life cycle. As mentioned before, some products are in fact chemical substances or preparations. Accordingly, the product as the object of analysis is not necessarily exclusive for LCA. However, the way in which a product is investigated in the two tools does differ, which will be investigated with respect to the following topics.

c. Large number of processes, chemicals, and impact categories involved
The large number of (industrial) processes, emitted chemicals to be assessed, and impact categories involved in this assessment, is quite specific for LCA. LCA tries to give an overall image of all quantifiable effects that are directly or indirectly caused by a product, including problem shifting to other chemicals, other impact categories or other stages of the product life cycle. HERA life cycles are typically restricted to one chemical and usually include fewer industrial processes, while only one or two impact categories are addressed. Although it may often not be feasible to perform a risk assessment on the same level as LCA in these respects, it is not impossible, at least in a theoretical sense. The number of processes, chemicals, and impact categories involved is therefore not a fundamental difference between LCA and HERA.

d. Range of impacts covered
HERA typically focuses on toxicity-related impacts, with respect to both human and ecosystem health. LCA has much broader ambitions, and typically includes in addition climate change, stratospheric ozone depletion, acidification, eutrophication, and even aims to include impacts related to land use and the depletion of resources (like minerals, fossil fuels, fish, and timber). Even though Cowell *et al.* (2002) consider the coverage of resources by LCA as 'the only aspect of the two approaches that is completely different,' we do not consider this as a fundamental difference. There is, by the way, a tendency to broaden the scope of HERA to include eutrophying impacts and impacts of desiccation (Latour *et al.* 1994).

e. Use of characterisation factors
Characterisation factors, which enable aggregation of the potential impacts of different chemicals, are very specific for LCA. In the end, however, they are not more than a technical aid. For human toxicity and ecotoxicity, characterisation factors form an intermediate step in the calculation of category indicator results, based on (time-integrated) doses and predicted exposures or environmental concentrations, respectively. It is very well possible to calculate these category indicator results directly, without the use of characterisation factors. Reversely, it is also very well possible to use characterisation factors in HERA for the calculation of risk characterisation ratios (RCRs), as will be shown in the next section.

f. Summation of effects of different chemicals
In the LCIA phase, the impacts of different chemicals that contribute to one impact category are summed up to one score for that category. Examples concern climate change, stratospheric ozone depletion, eutrophication, acidification, and a number of human and ecotoxicity categories. The procedure for this is as much as possible science based and used to be seen as a specific feature of LCIA. The reason behind it is based on practicality, rather than strict necessity. Without summation, a typical LCA study would deliver tens to hundreds of results, particularly for the human toxicity and ecotoxicity categories. For a contribution analysis (see, *e.g.*, Guinée *et al.* 2002) between different chemicals, this is indeed how LCA proceeds. For the comparison of product alternatives, however, it is more practical to end up with a limited number of results, consisting of an impact score of the product alternatives for each impact category as such. As mentioned before, recent developments include the construction of species sensitivity distributions (SSDs) for entire ecosystems (Udo de Haes *et al.* 2002; Posthuma *et al.* 2002). With this development, summation of chemicals is also getting within the reach of HERA (Traas *et al.* 2002), thus causing the summation of effects of different chemicals to be no longer specific for LCA.

g. Independence of time and location
In LCA, spatial and temporal characteristics were originally not accounted for. In Guinée *et al.* (2002), two spatial scales are distinguished for toxicological impact assessment with respect to environmental fate. This type of spatial differentiation is in accordance with the spatial differentiation in the EUSES model, the follow-up of the earlier USES model of RIVM (ECB 1997). Potting (2000) has even used a relatively very high grade of spatial differentiation by calculating characterisation factors for acidifying and some toxic chemicals for Europe on the basis of a 100× 100 km grid. Similar work has been done by Pennington *et al.* (2005), again for Europe. The influence of spatial variation of parameters on LCIA results is assessed by Huijbregts *et al.* (2003). Current LCA developments include the development of a global fate and exposure model (GLOBOX) that is differentiated at the level of separate countries, being the first impact assessment methodology that accounts for this type of differentiation (Wegener Sleeswijk 2003). At the same

time that we can observe increasing spatial detail in LCIA, we see that HERA is also performed at higher scale levels. As mentioned earlier, EUSES already includes the level of world regions. Similarly, MacLeod *et al.* (2001) present the regionally segmented BETR model for North America, Toose *et al.* (2004) extend this to cover the entire globe, and Wania and Mackay (1995) present another model covering the earth. Thus LCIA, starting at a global level, and HERA, starting at a local level, have met each other at the national/regional level. Temporal differentiation is sometimes accounted for in the inventory analysis of LCA (the LCI phase). No impact assessment methodology that accounts for this type of differentiation has been developed until now. In HERA, such as for instance in the EUSES model, however, temporal differentiation is not accounted for either. Hence, LCA also includes higher spatial resolution, and independence of time is thus not specific for LCA.

In relation to types of impacts, LCA looks both at medium and long-term time horizons, whereas HERA focuses on the short and the medium term. This largely depends on the types of substances involved, and is not a fundamental difference.

h. Emission pulses instead of fluxes
The production of a certain amount of a product corresponds to certain quantities of raw materials needed, and corresponding quantities of chemicals emitted to the environment (in kg). Such quantities (pulses) are usually assessed directly in LCIA, without accounting for the production capacities – and the connected emission characteristics – of the processes involved (in kg per year). In HERA, these production capacities and concomitant emission characteristics (fluxes) form the basis of the assessment. Although a bit unusual, it is possible to take the production flow of products (in functional units *per year*) – and the connected emission fluxes – as a starting point in LCA, instead of the products as such. Thus, even the alleged incompatibility between models based on emission fluxes (as in HERA) and models based on emission pulses (as in LCIA), already being resolved mathematically (Heijungs 1995), does not pose a fundamental difference between LCA and HERA.

i. Functional unit as a basis of assessment
This point has already been indicated in the introduction. The functional unit is the assessment basis of LCA, enabling comparison between different products that provide the same function. The products to be assessed thus are quantitatively characterised in terms of this function, for example '1 square meter of painted surface area during 10 years' in an LCA of paint. This makes it possible to account for differences in product lifetime or durability (one paint may last longer than the other) and efficiency (one paint may have greater covering power than the other). Processes throughout the product life cycle are quantitatively related to each other on the basis of their relative contribution to the defined functional unit. This implies that most processes – and the related emissions – are only partially included

in the analysis: so much electricity for this given functional unit, and not the electricity from one whole plant (Udo de Haes *et al.* 2002) in this context make a distinction between full mode of analysis (as in HERA) and attribution mode of analysis (as in LCA); see further in the Appendix. Both Olsen *et al.* (2001) and Wegener Sleeswijk *et al.* (2003) conclude that the functional unit can be considered as a key feature by which LCA fundamentally differs from RA.

j. Relative and absolute character of the assessment
Use of the functional unit as a basis for the modeling also determines another key characteristic of LCIA, that is, the relative character compared with the absolute character of HERA. As indicated in the introduction, Barnthouse *et al.* (1997) were the first to put this sharply. A functional unit usually is arbitrary in size; we could as well take 100 square meters to be painted, or 10,000 liters of milk to be packed, as long as it is the same size for all products to be compared. Instead, in HERA a fixed flow is taken as a starting point, usually the production volume of the chemical. This is transformed into environmental flows and concentrations, usually compared with given acceptable threshold flows or levels. HERA is therefore described as an absolute, 'only-above-threshold' approach. In contrast, LCA is in this context described as relative, 'less-is-better,' indicating the desirability of any decrease of hazardous substances, rather linking with prevention than with control.

We conclude that the latter two points, the use of the functional unit in contrast to actual flows, linked with the distinction between a relative versus an absolute modeling structure, fundamentally distinguish between LCIA and HERA. The other eight points are seen as secondary differences that in practice may occur to a greater or lesser degree. Besides these ten points, the literature mentioned earlier identifies a number of procedural differences as well. Among these are reporting formats, reviewing requirements, and the role in legislation. These type of differences have nothing to do with the model structure itself, and are therefore not discussed in this chapter.

3.3.3 Mathematical Analysis

Another way to analyse the differences between the tools is by means of symbolic language. In order to analyse mathematically to which extent observed differences are fundamental or not, it is first of all needed to phrase the tools in terms that are as much as possible similar. For instance, when it is said that LCA uses characterisation factors whereas HERA does not, it is necessary to investigate whether the tools do so for reasons that are primarily historical or practical, or for fundamental reasons. In the Appendix, we will show how the rephrasing of HERA-practice with characterisation factors helps to understand which differences between LCA and HERA indeed are fundamental and which are not.

Four differences are investigated mathematically: the use of a functional unit, the mode of analysis, the area, and the aggregation of impacts. The 'mode of analysis' is a new concept, introduced by Udo de Haes *et al.* (2000). It indicates the difference between full mode, where only processes in their full size are taken into account as in HERA, and attribution mode, where processes are taken into account only as far as they are related to a given reference as in LCIA. It is concluded that the first two are fundamental differences, the latter two secondary differences depending on the scope of the study.

3.3.4 In conclusion

Taking the results of the conceptual and the mathematical analysis together, we come to the following conclusion. The only fundamental difference between HERA and LCA is the use of flows of actual (or absolute) size in HERA and the use of the functional unit concept in LCA. In practice, this goes together with a difference between an absolute character of the analysis in HERA and a relative character in LCA. And in mathematical terms, this expresses itself in a difference between a full mode modeling structure in HERA and an attribution model modeling structure in LCA.

3.4 Level 3: applications

The third level deals with the application of the tools. If it is true, as concluded earlier, that the two tools cannot be fully integrated, this does not prevent combined use. On the contrary, it is the idea of a toolbox that a given decision can be supported by more types of information. Such a plea is for instance made by Wrisberg *et al.* (2002), Hofstetter and Hammitt (2002), Cowell *et al.* (2002), and Udo de Haes *et al.* (2004).

There are some clear examples of efforts to combine both tools. This can take different shapes. A first example of combines use concerns the study of Sonnemann *et al.* (2004). These authors compare two situations regarding the combustion of coal: situation 1 with the plant close to the mining site, in a very populated region, and situation 2 with the same plant farther away, in a less densely populated region, but in need of more transport. The results of the LCA study indicate that situation 1 is to be preferred, due to the lower energy demands for transport; whereas the results of the HERA study indicate that situation 2 is to be preferred due to the lower exposure of people to the plant emissions. The authors appear to be concerned about the differing results obtained with the two tools.

A second example concerns a study on insulation by Nishioka *et al.* (2002). The authors make a cost-benefit analysis to compare the current situation with respect to insulation of homes in the United States with a situation in which the complete housing supply would be heat insulated, according to a certain standard. For this purpose, they have constructed 'a model framework that allows for the evaluation of benefits combining risk assessment and LCA,' presented as 'an analytical framework that can incorporate Life Cycle impacts using a risk assessment framework' (p. 1004). Results are formulated in terms of energy savings, emission and risk reductions. No separate results are presented for the risk assessment and the LCA part: apparently, both tools have merged into a new analytical instrument.

A third example that underlines the usefulness of a toolbox approach, combining the application of both LCA and HERA, is provided by Saouter and Feijtel (2000), describing a case study comparing different detergent products from Procter and Gamble, in which a parallel ERA study and an LCA study are performed. These gave contradictory results; that is, of two products, the LCA study showed that for most of the impact categories product A had a lower score, whereas the HERA study showed that product B was to be preferred. But correctly, the authors argue that this illustrates the need to use complementary tools in the context of environmental management of chemical products. In fact, for the authors it is not astonishing that the results can differ, as the LCA study analysed the products from cradle-to-grave, and the HERA study focused on the waste management process only.

Recently, a follow-up of this study has taken place in the framework of the EU OMNIITOX project on the improvement of both LCA and HERA methodology (Pant *et al.* 2004). It concerns a new case study on detergents by Procter and Gamble, analyzing different outcomes of various LCIA models and an ERA model. Observing that the results of the different tools vary a great deal, the authors conclude: 'This puts a challenge to the OMNIITOX project to develop a method that finds common ground regarding fate and exposure as well as the effect side to overcome this situation of diverging results and to reflect realistic conditions as far as possible' (p. 281). So apart from the justified plea for a common ground at level 1, and despite the findings of their precedents, the authors of the secondary study seem to worry about the differing results of the HERA and LCA studies.

3.5 Discussion

So far, our findings can be summarised as follows. At level 1, the level of the basic equations, LCA and HERA show many similarities. The basic equations are essentially the same for both tools, be it that sometimes the spatial or temporal resolution will be different. The data on chemical properties and on environmental conditions are also essentially the same, although some differences are introduced, again due to differences in spatial or temporal resolution, and due to a difference in use (worst case vs. realistic case). At level 2, the level of the overall model structure, the two tools differ fundamentally on one point: the use of a functional unit in LCA in contrast to the use of processes in their full size in HERA. This goes together with the difference between a relative or an absolute approach, and a difference between an attribution and a full mode of analysis. This difference renders, at the level of the models underlying the tools as a whole, full integration of the two tools impossible. At level 3, the use of the two tools can be well combined in practice in the form of a toolbox.

This in fact is a rather simple message. But it is by no means supported by all authors in the field. Interestingly enough, in the example given on the integrated approach by Sonnemann *et al.* (2004) comparing two locations for one coal plant, the authors present the following interpretation of their result. They say that the result 'clearly demonstrates the need for a more integrated approach that does not so easily allow two environmental impact analysis tools to provide such contradictory and inconsistent results.' We do not agree with this interpretation; to put it in somewhat more challenging terms, we argue that only if two tools do produce independent, and thus possibly differing results, it is worthwhile to combine their use in a toolbox. Still, it is interesting to know whether Sonnemann *et al.* (2004) indeed achieved an integration of the two tools, a further aim of their study. Do they manage in this respect?

The procedure chosen by the authors is to make a distinction between impact categories at different spatial scales. Thus, impacts with a global reach such a climate change, are investigated by current LCA at a global level. In contrast, categories at a local level, such as human toxicity, are investigated at a lower level with a higher spatial resolution. This in itself is an interesting approach, compromising between the global and local requirements. However, we do not agree that this would imply an integration of LCA and HERA. The local analysis may be inspired by HERA due to its local focus, but the structure of the model is still straightforward LCA with its clear link to a functional unit as reference.

As to the example of the case study on insulation by Nishioka *et al.* (2002), the fact that these authors end up with a common, unambiguous result for their combined HERA/LCA study brings up the same question we asked earlier: Do these authors indeed achieve an integration of HERA and LCA?

Closer investigation of the study reveals that the authors have abandoned the usual functional unit concept. What they have done seems to boil down to the introduction of the life cycle concept in a combined *Risk Analy*sis/cost-benefit analysis context. The approach clearly differs from, for instance, the life cycle perspective in EUSES: not a chemical as such, neither a product, but a societal scenario (insulation of all homes) forms the object of the analysis. Although the study is quite limited in character from a conventional LCA point of view with respect to the number of life cycle processes actually involved, the number of emissions accounted for, and the refrain from the use of characterisation factors, it is interesting to see how near HERA and LCA could conceptually approach each other if applied to scenario analysis. The results are, however, presented in the form of risks. The absence of the functional unit makes it impossible to introduce this approach in the common LCA practice of general product assessment, and thus, to aggregate effects over the life cycle. Therefore, this study should in our opinion be considered as a modified form of risk assessment.

Yet another approach is followed in the case study on detergents by Pant *et al.* (2004). For the LCA part in this study, the system boundaries are limited to such an extent that they become the same as those for the HERA part. For both types of analysis only emissions to water during waste management are investigated. By doing this, we are not any more at the level of the models as a whole but just at the level of the basic equations. And at that level we fully agree that 'common ground regarding fate, exposure and effect modelling' should be achieved. And it is precisely at this level that the OMNIITOX project is due to produce very relevant results.

A last remaining question to be solved is, whether level 1 is indeed the limit for the integration of the two tools: Is the use of equal basic equations and equal input data the nearest point to which HERA and LCA could approach each other? If this were indeed the case, we might conclude that we are not far off from the maximum realisation of bringing HERA and LCA together. As stated earlier: HERA and LCA focus already on essentially the same chemical, toxicological, and ecological processes, and use the same relationships and data. Current LCA fate, exposure, and effect models are already being based on existing HERA concepts, also at level 1 of the basic equations and data. Is there nothing left to be possibly achieved?

We believe there is. The current problem with the discrepancy between LCA and HERA does not so much regard their structural difference, as discussed at level 2, but rather their lack of applicability as a combined tool. In principle, it is possible to apply both HERA and LCA to the same case, as becomes clear from some of the examples elaborated earlier. In practice, however, the implementation of such a combined case study requires a careful study process at all three levels. At level 1, it is not enough that the same equations and data can be used, but these must be used. At level 2, very specific methodological choices are required, aiming at a balance between the two tools. As we have seen earlier, these choices may easily cause one of the two tools to become subordinate to the other, or even to lose one or more of its essential features. And at level 3, yet another problem arises: the interpretation of seemingly conflicting results. Even to the experienced user in the field of either HERA or LCA it may be confusing if the outcomes of the studies suggest opposite solutions for the environmentally preferred choice. It may become fully unclear how to proceed, and the credibility of both tools among practitioners may be endangered. This situation should be avoided.

In their plea for a partial integration of LCA and HERA, Wegener Sleeswijk *et al.* (2003) propose 'that RA and LCA are to be incorporated in a common modeling tool, containing a common database. Such an overall modeling tool would deliver both risks of individual chemicals and impact scores for all LCA impact categories as outputs' (p. 86). In our view, the development of what we would like to call a 'combined software tool,' providing a harmonisation of equations and data where possible, and including the equations for the two tools in a balanced way, would probably be the best conceivable option to overcome the problems mentioned. In practice, the user of such a combined software tool could choose between two modes: either HERA or LCA, but within the same user-interface. If desired, the modes could be implemented both in consecutive steps, and the results could be compared in a scheme. The difference between the use of this common tool and the use of harmonised, but separate tools, would have implications for each of the three levels. At level 1, entry of chemical data by the user, and entry of model equations by the modeler, would be needed only one time, instead of two times as is the case nowadays. At level 2, differences would be pre-programmed as a number of consistent, but mutually exclusive options, whereas at level 3, the context in which the results are to be compared would be included as well.

In a combined software tool, the position of HERA and LCA in relation to each other may well be visualised as two cross-sections through the same apple: one may reveal a different rotten section than the other.

3.6 Conclusions

Although an increasingly clear picture was already arising on the links between HERA and LCA, a number of questions are in need of further clarification. What do the tools share, how far are they compatible, can they be integrated, and how is their relationship in applications? We addressed these questions by making a distinction between three levels of analysis: (1) the level of the basic equations to describe the environmental behavior and dose-response relationships of chemicals; (2) the level of the overall model structure of these analytical tools; and (3) the level of the applications of the tools.

Our findings can be summarised as follows. At level 1, LCA and HERA can make use of each other. The basic equations are in principle the same for both tools, be it that the spatial or temporal resolution may be different, and that there may be a difference between worst-case and realistic-case assumptions. At level 2, the two tools typically differ on many aspects, but the issue of the functional unit makes the tools fundamentally different, thus impeding full integration. This also expresses itself in a difference between an absolute versus a relative approach, and between a full-mode versus an attribution mode of analysis, as has been underpinned in mathematical terms. At level 3, the use of the two tools can be well combined in practice in the form of a toolbox. Even better would be the construction of a combined software tool, in which both models would be accommodated. With such a tool, it could become common practice to combine HERA and LCA, which could enable decision makers to weight the results against each other.

A number of recent cases seem to contradict these outcomes. In particular, some studies indicate the possibility of full integration of the tools as a whole, a conjecture that is contradicted by the present authors. With closer inspection of the given cases, however, we either observe that the suggested integration fully takes place in the framework of one of the two tools, or that it takes place at level 1 of the basic equations. In this way, the investigated cases in fact support the conclusions arrived at in the present contribution.

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Appendix: Mathematical analysis of HERA and LCA

In this annex a mathematical analysis will made of both HERA and LCA, identifying which differences between the two tools are fundamental, and which differences are only secondary depending on the scope of the given study. HERA and LCA can both be regarded as dealing with a phase of release assessment or inventory analysis, and with a phase of impact assessment. Let us start with HERA. In a given region, all activities that emit a specified substances (index s) to a specified compartment (index c) are taken into consideration. Assuming a continuous flow and a steady-state release, each process or activity (index p) can be specified as emitting an amount $\Phi_{s,c,p}$. The total mass flow or emission flux ($\Phi_{s,c}$; in kg/yr) is thus given by

$$\Phi_{s,c} = \sum_{p \in region} \Phi_{s,c,p}$$

Multi-media fate models, and in particular Type III multi-media models (Mackay 2001), possibly combined with exposure models, calculate a steady-state concentration in a number of target compartments or organisms (index t) from this. A usual and convenient simplification is that the relation between emission flux and steady-state concentration is linear, neglecting second- and higher-order kinetics. The proportionality factor for fate and exposure that connects for a specified substance release compartment c and target compartment or organism t, can be written as $F_{s,c,t}$, and the resulting steady-state concentration is

$$C_{s,t} = \sum_{c} F_{s,c,t} \Phi_{s,c}$$

Effect models translate this concentration into a response indicator on target compartment or organism t. An often-used method is to construct a risk characterisation ratio (RCR) as

$$RCR_{s,t} = E_{s,t} C_{s,t}$$

where $E_{s,t}$ measures the sensitivity of target t for substance s. A convenient choice is the reciprocal of the predicted no-effect concentration (PNEC):

$$E_{s,t} = \frac{1}{PNEC_{s,t}}$$

but indicators on the basis of species sensitivity distribution are becoming increasingly popular (Huijbregts *et al.* 2002). The combination of the fate/exposure and effect assessment can be written as

$$RCR_{s,t} = \sum_c E_{s,t} F_{s,c,t} \Phi_{s,c}$$

Then comes the LCA. The inventory analysis yields an inventory table, a list of quantified emissions (in mass terms: m) of specified substances (index s) to specified compartments (index c); hence $m_{s,c}$. Each entry of this list is an aggregation of the mass of substance s emitted to compartment c of each of the processes that are included in the product system. The mass emitted by each process is specified as

$$m_{s,c} = \sum_{p \in world} \Phi_{s,c,p} T_p \left(fu \right)$$

where T_p is the time that process p is active for the functional unit (fu) under study. In the characterisation step of the impact assessment, each mass release is multiplied by the appropriate characterisation factor $CF_{s,c,t}$ that connects substance s emitted to compartment c to target category indicator t. Furthermore, an aggregation over release compartments and substances is performed. Thus,

$$CIR_t = \sum_s \sum_c CF_{s,c,t} m_{s,c}$$

where CIR_t denotes the impact category indicator result for target organism or impact category t. For the purpose of comparison, we need to specify how a particular characterisation factor is constructed from a fate/exposure and effect model. In fact, this is the same model as that used for HERA, but with a unit release as input:

$$CF_{s,c,t} = E_{s,t} F_{s,c,t} 1$$

Entering this into the previous formula yields

$$CIR_t = \sum_s \sum_c E_{s,t} F_{s,c,t} m_{s,c}$$

Let us juxtapose the two equations for release and impact assessment of HERA

$$RCR_{s,t} = \sum_c CF_{s,c,t} \sum_{p \in region} \Phi_{s,c,p} \tag{3.1}$$

and for inventory and impact assessment of LCA:

$$CIR_t = \sum_s \sum_c CF_{s,c,t} \sum_{p \in world} \Phi_{s,c,p} T_p \left(fu \right) \tag{3.2}$$

We see the following similarities (*cf.* Tukker 2002):

- characterisation factor: HERA and LCA can use the same methodology for deriving characterisation factors (CF), and probably even the same lists;
- aggregation: HERA and LCA both aggregate over initial release compartments in calculating indicators.

We can also list the differences:

- area: HERA is often restricted to one region, LCA covers the whole world;
- mode of analysis, *i.e.* the difference between a full mode and an attribution mode* (Udo de Haes *et al.* 2000): HERA takes all activities in this region fully into account, LCA takes activities into account as far as they are needed for the functional unit
- aggregation: the result of the HERA is an indicator (RCR) per target compartment (t) per substance (s), the result of LCA is an indicator (CIR) per target compartment (t), but aggregated across substances;
- units: the time factor (T) included in the LCA-formula makes the difference in units between the result of HERA and that of LCA.

Of the four differences identified above, the mode of analysis and the functional units are fundamental differences that arise from differences in goal, while the area and the aggregation are secondary differences, arising from differences in scope. Both fundamental differences are directly related to the functional unit concept.

It has been noted that the choice of a certain region for HERA is usual, but not mandatory. In principle, one may choose the world as the region here, in which case this difference disappears. As to the aggregation, measures of toxic pressure as the result of a number of chemicals is increasingly becoming available (Traas *et*

* The dichotomy introduced here between including a process in its full extent and including it only for a part has been described at various places under various names. Udo de Haes *et al.* (2000) approach it from the technical side and use the terms full-mode and attribution-mode. Heijungs (2001) speaks of commodity-flow accounting and activity-level analysis. Barnthouse *et al.* (1997) approach this dichotomy from the consequence side and uses the terms absolute and relative to indicate these two modes. Likewise, Olsen *et al.* (2001) employ the terms absolute and comparative. Below, we will further use the terms of Barnthouse *et al.*, absolute and relative, relative meaning in relation to a functional unit.

al. 2002). Supposing both aspects would change, the basic equation for HERA would become

$$RCR_t = \sum_s \sum_c CF_{s,c,t} \sum_{p \in world} \Phi_{s,c,p} \qquad (3.1')$$

and the only difference with the basic equation for LCA, Equation (2) is the presence of the factor $T_p(fu)$, expressing the relation with the functional unit. See also Table 3.1.

Table 3.1 Overview of differences between the model structure of LCA and HERA at the conceptual and mathematical level.

conceptual analysis		mathematical analysis	
#	aspect	LCA (Eq. (3.2))	HERA (Eq. (3.1) and (3.1'))
a)	life cycle perspective	$\sum_p$	$\sum_p$
b)	product as object of analysis	–	–
c)	number of processes, chemicals, and impact categories involved	–	–
d)	range of impacts covered	–	–
e)	use of characterisation factors	*CF*	*CF*
f)	independence of time and location	–	–
g)	summation of effects of different chemicals	$\sum_s$	– and $\sum_s$
h)	emission pulses instead of fluxes	T_p	–
i)	functional unit as a basis of assessment	*fu*	–

In conclusion: what rests from this mathematical analysis as fundamental difference is the use of the functional unit and the mode of analysis (*i.e.*, the difference between a full mode and an attribution mode). Obviously, the two are related: the presence of the time factor (T_p) in the LCA-formula marks the difference in unit. And in its turn, the time factor has been introduced to be able to connect activities and emissions to products by means of the functional unit. Thus, the ultimate difference between the overall model structure of LCA and HERA concerns the use of a functional unit in LCA (*cf.* Olsen *et al.* 2001, Wegener Sleeswijk *et al.* 2003), and in line with that the use of the attribution mode of analysis mode of analysis (Udo de Haes *et al.* 2000).