Titre: Title:	Spatial differentiation in LCA :Moving Forward to More Operational Sustainability
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Date:	2007
Type:	Article de revue / Article
Référence: Citation:	Sedlbauer, K., Braune, A., Humbert, S., Margni, M., Schuller, O., & Fischer, M. (2007). Spatial differentiation in LCA :Moving Forward to More Operational Sustainability. Lebenszyklusanalysen in der Nachhaltigkeitsbewertung, 16 (3), 24-31. https://doi.org/10.14512/tatup.16.3.24

Document publié chez l'éditeur officiel
Document issued by the official publisher

Titre de la revue: Journal Title:	Lebenszyklusanalysen in der Nachhaltigkeitsbewertung (vol. 16, no. 3)
Maison d'édition: Publisher:	TATuP
URL officiel: Official URL:	https://doi.org/10.14512/tatup.16.3.24
Mention légale: Legal notice:	

Spatial Differentiation in LCA
Moving Forward to More Operational Sustainability

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Life cycle assessment studies (LCA) according to ISO 14040 and ISO 14044 and using generic data (i.e. without regard for geographic variability in the life cycle inventory <LCI> or life cycle impact assessment <LCIA>) are well adapted to evaluate environmental impacts from a global perspective. For impact categories that are not global in nature such as acidification, eutrophication, or toxicity, the use of generic data can lead to results that do not reflect the impacts accordingly. Clearly, the need for spatial differentiation depends on the scope and boundaries of the study. However, when assessing LCIs from different regions, or when geographical conditions of the emission location are known, regionalization might increase the discriminating power of LCIA. Future research should be focused on developing guidelines identifying when spatial differentiation is relevant, what type of differentiation is needed, and on generating and linking compatible LCI and LCIA that are both geographically specific to continents (for political reasons this is more accepted) and situation dependent to better reflect local variations.

1 Spatial differentiation in LCA: Pure curiosity or necessity?

1.1 Looking to the past

To identify and assess the environmental impacts of goods and services from a holistic viewpoint, life cycle approaches embrace various studies and methods for decision support, from detailed quantitative life cycle assessment (LCA) to qualitative screening. Originating as technology assessments, the first studies were carried out in the late 1960s. Over the last three decades, LCA has developed dramatically. This development includes a shift from pollution prevention and gate to gate concepts to a holistic view, including both the supply chain and downstream processes. Starting with pure mass-based assessments, nowadays LCA takes more and more environmental issues into account. Early LCA studies only included inventory information, resulting in far too simplistic mass and energy balances. With a holistic view, LCA can be a suitable tool for integrating product-related environmental aspects into decision making in industry and for identifying environmental hot spots, opportunities, and trade-offs for policy making (Hunkeler and Rebitzer 2005).

1.2 LCA and sustainability

In 1987 the Brundtland-Report stated that sustainable development "meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987, S. 54). Thereby, the three pillars of sustainability are the environmental, economic, and social aspects. As sustainability is by its nature a global issue, its assessment needs to provide a global coverage, including aspects independent of space or region as well as spatially dependent aspects. Cultural variations, country specific differences in environmental consciousness, or social issues may affect sustainability priorities. When using LCA in sustainability assessment, these effects hold true for indicator development, the availability of datasets, and the type of studies being chosen by practitioners. From an environmental point of view, the main influencing factors with regard to space include technology standards, climatic differences, biosphere conditions, and resource availability. Therefore, the future orientation of spatial differentiation as an assessment tool with a global perspective needs to be discussed.

1.3 Spatial differentiation: Why does it matter?

Today the application of LCA is widespread in industry, research, and policy for various reasons. Industry's interest in including LCA as a decision making tool is mainly motivated by product improvement, green product design, or gaining insight into a product's environmental behavior in comparison with other products. On the one hand, research on LCA is currently shifting more and more to application related questions. On the other hand, inventory data is becoming more and more detailed and impact assessment methods are becoming more refined and extended to a greater coverage of substances. One also observes that the greater the consensus between practitioners and researchers, the more LCA is used in policy making. Real environmental benefits can only be achieved, however, if LCA is applied correctly. This is why the research should be in line with the needs of LCA practitioners. Regarding spatial differentiation, the needs of LCA practitioners must be known in order to provide useful and valid results. For practitioners and inventory and impact assessment experts, the following questions outline the scope of future work in this area:

- What level of spatial resolution is environmentally relevant?
- What is practically affordable and feasible in terms of data gathering and data processing?
- What are the benefits vs. the additional work for LCA practitioners?
- How can global consistency and coverage be fulfilled?

LCA researchers, especially in impact assessment, realized that the total exclusion of spatial information from LCA characterization can lead to invalid results (Potting, Hauschild 2006). Finding consensus on inventory aspects, such as the definition of environmental interventions, has made spatial differentiation in LCA a timely topic.

2 State of the art

2.1 Applying life cycle approaches – The LCA practitioner's point of view

Since the ultimate goal of research on LCA is its application, the practitioner's point of view is elaborated in greater detail. Generally spoken, LCA results are used in the following cases: Global exploration of options, internal innovation at the company level, sector driven innovation, strategy determination, comparison between alternatives, comparative assertion disclosed to the public (Guinée et al. 2002). Are spatially differentiated results requested in each of these cases? The following subchapters show some examples.

2.1.1 Global and regional exploration of options

The European Commission currently supports and carries out the three "IMPRO-projects":

- Environmental Improvement Potentials of Residential Buildings (IMPRO-Building),
- IMPRO-Car,
- IMPRO-Food.

Within these projects, improvement potentials are found for the respective products (buildings, cars, food) from a European perspective using LCA. As for the IMPRO-Building project, LCA studies for more than 70 building types are carried out, based on a survey and technical description of representative residential building types from the 25 EU countries (Environmental Improvement Potentials of Residential Buildings (IMPRO-Building), 2007). The environmental improvement potential of refurbishment options or new construction alternatives is then defined as the difference between today's baseline scenarios and the "improved scenarios". Spatially differentiated results are given for three zones, inventory data for the foreground system is applied to the three zones and most of the background processes is consistently the European average. The impact assessment is carried out on global level.

2.1.2 Internal innovation at the company level

LCA studies are widespread in various sectors and carried out to support eco-design in companies. Multinational companies with a wide sphere of influence tackle issues that are very much motivated by specific regional problems. Therefore, LCAs on internal innovation should answer questions regarding, for example infrastructure, transportation, local technology levels, and the condition of the surrounding environment, which are directly linked to the company site. A global overview of all regionally differentiated impacts is not necessary.

2.1.3 Sector driven innovation

Germany's Ministry of Education and Research initiated a project on environmental potentials for wood products called "ÖkoPot". This project identifies wood products that, if used to replace products with a greater environmental impact, could significantly reduce the environmental load released in Germany. Focusing on one country, imports and exports of respective materials play a role in the products' inventories and averaging transport distances, technologies and background processes. For sectors, a country's borders define the system boundary for which direct influence is given.

2.1.4 Strategy determination

Timely examples for strategic decisions supported by LCA are, for example, projects related to the use of biofuel for transportation. Companies, associations, and other stakeholders are involved in these projects with significant potential implications for societies. The differentiation of results with regard to location is currently broken down at the country level. The identification of where to produce biofuel can and should be based on spatially differentiated information in order to consider local conditions.

2.1.5 Comparison and comparative assertion disclosed to the public

The direct comparison of products' environmental profiles heavily depends on the underlying system boundaries and the assumptions made regarding spatial information in the inventory. Environmental Product Declarations, according to ISO 14025, represent a consistent and valid communication instrument for company specific products and are used for direct comparisons or in overarching assessment schemes (e.g. building sustainability assessment). The purpose of such declarations is often to communicate the companies' efforts to reduce emissions and resource consumption. With regards to impact assessment, generic characterisation factors may draw attention away from the effort the company is making. A characterisation factor converts the inventory result (e.g. kg CH_4 emitted) to a common unit of an impact category indicator (e.g. kg CO_2-equivalents). It represents the environmental mechanism.

2.2 Accounting for environmental interventions – The life cycle inventory point of view

Within the life cycle inventory (LCI), the interactions of a system with the environment are assessed on material and energy levels. Resource extractions from the environment and emissions to the environment are both quantified. Regional differentiation is already part of LCI modeling as, for example, the production of many products is assessed country specifically, e.g. country specific power grid mixes (country specific electricity generation). Inventories, characterized by elementary flows (materials / emissions or energy exchanged between the system and the environment), generally do not contain the information on where the elementary flows are emitted. This holds especially true for the output side. On the input side, some data providers create inventories with country specific resource extraction elementary flows due to different physical and chemical properties, e.g. crude oil from Venezuela.

Some inventories currently try to address the receiving compartment more specifically, e.g. copper ion to groundwater. Recently, a project for a general, valid elementary flow list has begun, initiated by the European Commission (European Platform on LCA 2007). From the inventory side, what is now needed is a comprehensive, easily manageable, and meaningful spatial differentiation of single processes within a process chain, and a documentation of the spatial aspects that is in line with data management possibilities and the extra effort.

2.3 Assessing environmental effects – The life cycle impact assessment point of view

The purpose of life cycle impact assessment (LCIA) is to assess the significance of potential environmental impacts of each elementary flow of the life cycle inventory (LCI) for each relevant impact category. The results of a LCIA are expressed through what is known as an environmental profile, where the LCI is grouped in a reduced number of indicators (impact categories). Within the conversion of LCI to LCIA, characterization factors are applied to get results with a common unit (see also ISO 14044)

The development of generic characterization factors (CF) in LCIA has been historically motivated by the lack of spatial and temporal information when collecting LCI data for a given product system. Though several LCA software programs do allow the inclusion of geographical information, this feature is still not always taken advantage of. These generic CFs are well adapted to evaluate global impacts, such as global warming and ozone layer depletion, but have some inherent limitations when assessing those impact categories that are not global in nature, such as acidification or eutrophication, which are typically regional impact categories with continental coverage. Photochemical ozone formation or respiratory effects from airborne pollutants, and resource related impact categories such as land use and water use are considered even more local (down to a few kilometers). Toxicity and ecotoxicity impact categories, however, can range from very local to global impacts, depending on the substances.

The main reasons for addressing spatial differentiation are 1) to learn about the uncertainty linked to the spatial variability of generic CFs and 2) to identify what the appropriate scale for LCIA, and thus LCI, is.

Global impacts do not need spatial differentiation. Regional and local impacts will benefit from increased precision and reduced uncertainty, given spatial differentiation. However, since local impacts can vary within a few kilometers, the spatial resolution needed to capture such differences might be extremely high. This can be an issue since 1) an enormous amount of geographical data (local population density, wind direction, etc.) is required for the modeling of the CFs, 2) even if the geographical data are available and the CFs are generated, storing these thousands or even millions of CFs in LCA software can create storage capacity issues, 3) linking these CFs to inventory results can become extremely difficult, and 4) this enormous amount of data quickly impedes any reasonable analysis and quality check.

Hence, practical solutions have been found: the approach of situation dependent versus geographically differentiated solutions.

- *Geographically differentiated* refers to the differences between geographical locations such as continents, countries, or regions throughout the world, e.g. South vs. North America, Germany, North Sea, etc. The geographical location where the impacts occur is sometimes captured in the information related to where the supply of the material or product is from, e.g. crude oil from Venezuela.
- *Situation dependent* refers to archetypical situations leading to important variations in the characterization modelling and its results and therefore justifying a differentiation. It then refers to the type of environment the pollutant is emitted into or where the inventory flow is occurring, e.g. high vs. low population density area, agriculture intensive area, upstream vs. downstream of a lake.

Regional impact categories are well modeled using geographically differentiated information. However, local impact categories are better modeled using situation dependent information.

One of the issues that often arises is the inconsistency between practitioners' worries and scientific reality. Indeed, different countries often face different environmental problems and priorities. However, for more local impacts, it is common to observe that the variability of impact indicators within the country is often more important than the variability between countries. These situations need to be explored and clearly identified by LCIA. LCIA needs to explain to the practitioner what the relevant scales to use are, which type of spatial differentiation is needed in respect to the uncertainty that can be afforded. However, LCIA also needs to provide CFs for regions or situations that may not be defined using the most relevant borders (e.g. CFs modeled for countries) but that were defined based on the scope of the practitioner.

Table 1 presents the most common impact categories normally considered in LCIA, distinguishing between type of impact (global, regional, local) and possible archetypical situations.

Table 1: Different impact categories along with the type of impact and possible archetypical situations

Impact category	*Type of impact*	*Type of region or archetypical situation that could be considered*
Human toxicity (carcinogens + non-carcinogens)	Local	Air emission: High vs. average vs. low population density (for pollutants dominated by the inhalation pathway); Intensive vs. extensive vs. non-agricultural region (for pollutants dominated by the food pathway); Off-shore Water emission: Upstream vs. downstream of a lake; Ocean vs. lake vs. river Soil emission: Agricultural vs. non-agricultural soil
Respiratory effects caused by inorganics	Local	Air emission: High vs. average vs. low population density; Off-shore
Ionizing radiation	Local	Air emission: High vs. average vs. low population density (for pollutants dominated by the inhalation pathway); Intensive vs. extensive vs. non-agricultural region (for pollutants dominated by the food pathway); Off-shore Water emission: Upstream vs. downstream of a lake; Ocean vs. lake vs. river Soil emission: Agricultural vs. non-agricultural soil
Ozone layer depletion	Global	-
Photochemical oxidation	Local	Country; High vs. average vs. low population density
Aquatic ecotoxicity	Local	Air emission: Country; Off-shore Water emission: Upstream vs. downstream of a lake; Ocean vs. lake vs. river Soil emission: Type of watershed
Terrestrial ecotoxicity	Local	Air emission: Off-shore Water emission: Upstream vs. downstream of a lake; Ocean vs. lake vs. river Soil emission: Agricultural vs. non-agricultural soil
Terrestrial acidification/nutrification	Regional	Air emission: Country/continent Soil emission: Country/continent; Type of soil
Aquatic acidification	Regional	Air emission: Country/continent Water emission: Upstream vs. downstream of a lake; Ocean vs. lake vs. river; Type of lake
Aquatic eutrophication	Regional	Air emission: Country/continent Water emission: Upstream vs. downstream of a lake; Ocean vs. lake vs. river; Type of lake
Land occupation	Local	Type of land; Country; Type of ecosystems
Biodiversity loss	Local	Type of land; Country; Type of ecosystems
Global warming	Global	-
Non-renewable energy	Global	Country (especially related to social issues)
Mineral extraction	Global	Country (especially related to social issues)
Noise	Local	High vs. average vs. low population density
Accidents	Regional	Country / continent

Source: own compilation

3 Expectations, prospects and current developments

3.1 Practitioner expectations

There is an increasing demand on LCA practices to reflect regional concerns. It is not surprising that practitioners are reluctant to apply LCI databases and LCIA methodologies developed for example for a European context to evaluate a product manufactured in South America. From the practitioner's point of view, the integration of spatial differentiation in LCA should fulfill the following requirements:

- affordable,
- easy to include in existing methodology and software tools,
- easy to use when carrying out LCA studies,
- results are easy to interpret,
- data is available.

Differentiating foreground and background processes along with geographic specifics and/or situation dependent flows might be a first and important step.

3.2 Possibilities and restrictions for LCI and LCIA experts

From the inventory point of view, the possibilities of differentiating the spatial resolution include obtaining more detailed and significant results, considering more specific boundary conditions and regional distinctiveness, using region-specific analysis, evaluation, and interpretation, and developing LCA methodology. On the other hand, restrictions include the manageability of data collection and data handling, consistency in data collection, modeling and interpretation, and comparability of results. Several commonly used simplifications in LCA methodology are no longer valid. Data management is considered a significant challenge for LCI experts when discussing spatial differentiation.

LCIA information without a direct link to LCI result tables for product systems is useless. Thus LCIA must be compatible with LCI in order to interpret the information provided by the LCI correctly and to provide the best analysis possible due to this information. However, to be relevant, the LCI should be designed based on LCIA recommendations. Indeed, LCIA makes possible the identification of the relevant issues that should be considered when evaluating the impacts associated with a unit process of a given product system. Thus LCIA tells the practitioner and LCI experts if and what type of spatial differentiation is needed in relationship to the affordable uncertainty.

3.3 Current developments in the field of natural science and data organization

Further developments in data organization will require that comprehensive databases on LCI (process information) and LCIA (characterization factors) are currently available and comprehensive software tools to model and evaluate LCA are in use. Data providers are conscious of the fact that more information related to spatial differentiation should be included in an “intelligent and sustainable” way to ensure ease of use and interpretation. However, further integration of information still needs to be discussed with regard to the effort required to gather the data and to restrictions associated with data management. For this under the umbrella of the LCIA program of the UNEP / SETAC Life Cycle Initiative a working group on spatial differentiation was recently launched.

Current LCIA methodologies have been developed to assess emission inventories for specific regions such as Europe (e.g., IMPACT 2002+ – Jolliet et al. 2003; Eco-indicator 99 – Goedkoop and Spriensma 2000; CML – Guinée et al. 2002; EDIP 2003 – Hauschild et al. 2006), the US (TRACI – Bare et al. 2003), Canada (LUCAS – Toffoletto et al. 2006), and Japan (LIME – Itsubo and Inaba 2003). The lack of models adapted to other regions, and especially to developing countries, is considered as a political and scientific limitation of the current impact assessment practices (Humbert et al. 2007c).

Several studies have addressed spatial modeling in LCIA: acidification and eutrophication (Potting et al. 1998; Huijbregts et al. 2001; Norris 2002; Seppälä et al. 2006), human toxicity (MacLeod et al. 2001; Pennington et al. 2005; Toffoletto et al. 2006), respiratory effects caused by primary and secondary particles (Humbert and Horvath 2007b), and photochemical smog formation (Hauschild et al. 2006). The scale of regionalization can vary from continental resolutions (Toose et al. 2004; Rochat et al. 2006) down to 200 km x 200 km and 50 x 50 km for human toxicity and ecotoxicity, and acidification and eutrophication, respectively.

Current projects for human toxicity and ecotoxicity are under way for North America, aiming at the same spatial resolution as mentioned above (200 km x 200 km) (Humbert and Horvath 2007a, Manneh et al. 2007) and in South America at a lower resolution (1000 km x 1000 km) (Maia de Souza et al. 2007). Resource related impact categories are still poorly evaluated with regard to spatial issues.

4 Summary and outlook

It has been proven that spatial differentiation or regionalization can increase the discriminating power of LCA. Depending on the impact category, the variability could be up to two orders of magnitude when assessing generic emission inventories from different continents. Additional variability of up to two or three orders of magnitude can be reached when the exact emission location is known (Humbert et al. 2007c). However, regionalization is not always needed, and depends on the goal and scope and system boundaries of the study. It can become a necessity in some specific cases, for example when:

- the LCA is performed using life cycle inventories differentiating emissions from different continents,
- assessing specific key processes dominating the overall life cycle impacts and for which the exact emission location is known,
- for further application such as cost-benefits analysis, environmental justice or environmental impact assessment.

Current efforts should focus on identifying when regionalization is really needed and on developing clear guidelines and solutions for data gathering for the inventory and the development of characterization factors (CF) that are both situation dependent and geographically differentiated. Advances in regionalization should also concentrate on developing countries. The development of situation dependent CFs that are valid independent of the continent studied should be prioritized in order to capture the major differences in archetypical situations, while still keeping the number of geographically differentiated CFs restricted.

If implemented accordingly, these developments can greatly improve the acceptance of LCA results, and reduce uncertainties associated with comparative studies between continents or between regions with different priorities and geographical conditions.

Note

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