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Arbeitskreis METHODIK

Modelling of product systems in life cycle inventory anlysis: Synopsis of Attributional and Consequential LCI Models – Properties and Differences

Projektbericht

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Modelling of product systems in life cycle inventory analysis: Synopsis of Attributional and Consequential LCI Models – Properties and Differences

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Purpose of this paper

This paper describes the state of discussions with regard to product system modelling in life cycle inventory analysis. It serves as the basis for discussions on recommendations towards the German network on life cycle inventory data.

Introduction

In the last nearly ten years a dependence of LCI concepts and models on the LCA goal has been identified (Curran et al. 2002; Ekvall et al. 2004; Ekvall & Weidema 2004; Frischknecht 1998; Udo de Haes & Wrisberg 1997; Weidema et al. 1999). One main distinction is made between models that describe a state of the flows of the economic system (attributional LCI) and models that describe changes in the flows within the economic system caused by a decision made or planned (consequential LCI). A second major distinction covers the time aspect. LCIs may be retrospective (describing past situations or changes) or prospective (describing expected situations or changes).

The paper concentrates on the differences between attributional and consequential LCI models.

LCA concepts for reporting and for decision-support

The attributional approach

The outline of attributional LCI models has been described in depth by Heijungs (1997). Attributional LCI models may be used to describe for instance the life cycle of one litre of fair trade orange juice consumed in the European Union in 2003. It is assumed that this litre is part of the total consumption volume of juice in EU (1'900 tons of juice concentrate) and not an extra litre. Inputs and outputs will be determined based on the average production situation for the total amount sold in

2003. The product system of such an attributional analysis comprises (theoretically) all farmers involved in harvesting oranges under fair trade conditions, all factories producing fair trade orange juice in 2003, all factories producing packaging materials for this juice, *etc*.

The result of such an LCI (or LCA) provides information about the environmental impacts of farmers, producers, carriers, *etc*. that can be attributed to the consumption of an average litre of fair trade orange juice purchased in 2003.

The consequential approach

The outline of LCI models that describe the changes of a situation caused by a decision, called "consequential approach", has been extensively discussed during an LCA workshop on electricity data in LCI held in Cincinnati, Ohio, USA and during the Internet Life Cycle Assessment - Life Cycle Management (InLCA-LCM) conference in May 2002 (Ekvall 2002). Furthermore, papers have been published by (Ekvall et al. 2004; Ekvall & Weidema 2004). In the final report of the electricity workshop Curran et al. (2002) the consequential approach is defined as an attempt to estimate how flows to and from the environment will *change* as a result of a decision. A consequential LCA aims to answer the question whether the decision to purchase for instance a litre of fair trade orange juice (instead of conventional orange juice, instead of apple juice, instead of tap water, *etc*.) leads to reduced or increased CO_2-emissions, nitrate and pesticide emissions to water, *etc*. on a global level. For that purpose, factories and farmers need to be identified which will change their production volume due to that particular change in demand. Opposite to the attributional approach, actors (farmers, producers, carriers *etc*.), that are not affected by a change in that demand, are not part of the product system of a consequential LCA.

In other words, the product system does not comprise the world average of orange farmers but the ones that will increase or decrease their production. It may well include apple farmers as well, if an increase in fair trade orange juice consumption is at the expense of apple juice. It may even include (selected) conventional orange farmers (and no fair trade farmers) if the production capacity of fair trade farmers is constrained. In that case, a decision to purchase fair trade orange juice instead of apple juice leads to increased sales (and production) of conventional orange juice, because sales of orange juice as a whole increases but fair trade farmers cannot supply the additional demand. Hence, the additional litre of fair trade orange juice would then be charged with the environmental impacts of an additional litre of conventional orange juice.

We recognise that the consequential approach aims to link micro-economic actions with macro-economic consequences (what happens in the different markets that are affected by my decision?). It requires an LCA that considers market reactions, production volume developments, technology developments *etc*. This information may be delivered by a set of (pre-defined) conditions, by one or several scenarios or with the help of dynamic models. In any case an embedding in a broader range

of socio-economic interdependence is required. The hybrid LCA developed at CML and presented at the Swiss LCA discussion forum No. 16, held in April 2002 (Suh 2002), may be an option in describing the LCA system embedded in a broader socio-economic interdependence for a complex modeling. It can be non-linear, it can consider capital inducement and it can be extended to computational general equilibrium (CGE) models.

The result of a consequential LCI provides information about how an individual (consumption or investment) decision will influence the (global) environment and whether the purchase of a supposed environmentally friendly product is likely to lead to a reduction in overall environmental impacts.

An alternative definition of the consequential approach: the decisional approach

An alternative definition of the consequential approach remains on the micro-economic level and is described in Frischknecht (1998). It is called *decisional* approach in this paper. In contrast to the interpretation of the consequential approach described above, the decisional approach uses the financial and contractual relations between economic actors (b2b relations) as the main basis of information. Applied on our case study, namely the decision whether or not to buy fair trade orange juice (instead of conventional orange juice or instead of apple juice), the product system would be modelled as follows: If a consumer chooses to purchase a certain (labelled) product or service he or she is entitled (or obliged) to accept the environmental impacts that are economically and contractually related to its production.

As a consequence - and this is the main difference to the consequential approach described above -, the orange juice LCI includes fair trade farmers, producers, carriers, *etc.* in any case, even if they were not able or not obliged to adjust their total production (my extra consumption might be compensated by a reduced consumption by someone else). The decisional approach attributes particular economic activities, that are linked to the product via economic and contractual relations, to an individual additional (or reduced) consumption. The consequential approach as defined in the previous section links a (consumption or investment) decision to its affected economic activities irrespective of the fact whether these affected activities are actually required for the product consumed or invested in, and irrespective of the fact whether direct economic and/or contractual links to the purchased product exist.

The alternatively defined consequential LCA supports an efficient allocation of scarce environmental resources (similar to the price system, that helps to allocate the traditional economic resources labour, land and capital). This alone of course does not reduce environmental pressure. Supporting measures introduced on a macro-economic level are of course necessary. An environmental policy is required that defines reduction targets on emissions and resource consumptions or on environmental impacts (such as global warming). The relative scarcity of the

environmental resources can then be operationalised for LCA with the help of life cycle impact assessment methods.

The need for scenarios in prospective LCAs

If we conduct a prospective LCA, scenarios are required irrespective of the concept applied. However, the breadth of required scenario information differs substantially. In a prospective *attributional* LCA, predictions about technology development, about technology mixes, and average supply situations in the relevant moment in time are required. Hereby information is required for all technologies that contribute in relevant portions to future mixes.

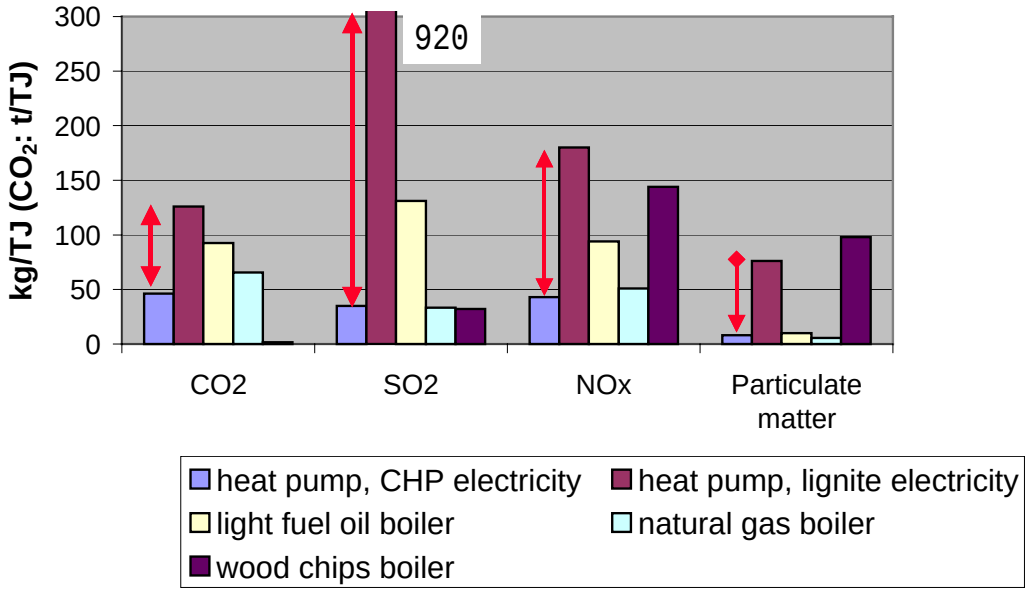
In a prospective *consequential* LCA predictions about technology development are also needed but only for marginal technologies (technologies/production sites that change their output or are put in or out of operation due to a macro-economic change in demand). Additionally, macro-economic information such as the developments in relevant markets (whether growing, saturated, or shrinking), about marginal technologies and marginal production sites, about final consumption levels, economic growth rates, and eventual market constraints are required.

In a prospective *decisional* LCA, information about the future economic relations of the actors involved in the product system at stake is required. The more distant an actor is located in the supply chain of a product or a service, the more difficult it will be to get the required, specific information. One source of information is the periodical publications on market developments and forecasts. Relevant technology mixes may be identified based on such information. With respect to far distant suppliers, and with respect to unspecific purchases of commodities, the decisional and the consequential approach are rather similar. If however, a specific and labelled commodity is purchased, the two approaches differ substantially.

The fact that consequential and partly decisional approaches require scenario information on future developments makes LCAs based on these approaches dependent on the choice of such scenarios. An example on an investment decision is used to illustrate the scenario dependency. The question is whether or not to buy an electric heat pump for domestic heating. Alternative technologies are light fuel oil, natural gas or wood chips boilers. In the consequential approach one needs to know the future developments in the electricity market. In particular the question whether the market volume grows or shrinks is of decisive importance. In case of a shrinking market, the (economically) least efficient power plants, i.e. the ones with the highest operational costs, will be shut down. In case of an expanding market, the (economically) most efficient power plants, i.e. the ones with the lowest total costs per kWh, will be installed instead. The most inefficient power plants may be fuel oil power plants whereas the most efficient ones are gas-fired gas combined cycle power plants.

The life cycle emissions of heat pump heat varies dramatically depending on the assumed future development of the electricity market (see Fig. 1). While heat pumps running with GCC electricity show lower cumulative emissions compared to competing boiler systems, the same heat pump operated with electricity from fuel oil power plants performs worse.

Fig. 1 **selected cumulative life cycle inventory results of the supply of 1TJ useful heat with different domestic boiler systems**



The modelling of multifunctional processes and of recycling

According to (Ekvall & Weidema 2004) the allocation problem in multifunctional processes and in open-loop recycling is automatically solved with system expansion when applying a consequential modelling approach. Firstly, the co-product of interest of the multi-functional process is determined. Secondly, marginal products or production technologies are identified for all other co-products. These marginal products and production technologies are then considered in system expansion instead of assuming average production patterns as is mostly done in attributional LCAs. The environmental impacts caused by the supply of these marginal products and the marginal production technologies, respectively are determined with a life cycle perspective. They are subtracted from the total environmental impacts caused by the multifunctional process.

Marginal products are defined as the specific products that are most likely coming to the market if the demand is increased (or which disappear from the market due to decreased demand). The same view can be applied to production technologies. The marginal production technologies are defined as the specific technologies that are most likely to increase their production if the demand is increased. For defining these products or production technologies very good knowledge on market developments, price elasticies and market restrictions is necessary.

One main point of critique is the fact that the environmental impacts caused by these marginal products or production technologies are fully attributed in the form of a credit to the multifunctional process or the life cycle that supplies materials to be recycled. As has been pointed out by Frischknecht & Jungbluth (2003) the avoided burden approach helps to identify the maximum environmental benefit of co-production. But it does not avoid allocation because (at least) two parties may claim this environmental benefit. On the one hand the one that is operating the multifunctional process and on the other hand the one that purchases co-products manufactured in this multifunctional process. The same applies in recycling: the ones that supply and purchase material to be recycled may claim the environmental benefit of doing so. Hence, the total environmental benefit needs to be split between these economic actors. The automatism to attribute the entire environmental credit to one of the two leads to an unbalanced view and may even lead to an omission or to a double counting of actually occuring environmental impacts. The avoided burden approach may be useful in national environmental accounts where it is not a matter of attributing enviornmental impacts to particular products or services but to quantify the annual national impacts in total. Furthermore it helps to identify the maximum achieveable environmental benefit. However, it does not avoid the allocation step as the credit still needs to be shared among the concerned parties.

Summary

Tab. 1 shows the main characteristics of the three approaches described above. We have seen that three main modelling principles may be distinguished, namely the attributional, the consequential and the decisional approach.

All approaches may be applied in a past or future situation. The attributional approach is used in reporting and the inventory model (the product system) is based on economical and/or contractual relations. The consequential approach is used for decision support (past and future) and the relations are identified with the help of computational general equilibrium models. The decisional approach is also used in decision support but the inventory model is based on future or planned economic and/or contractual relations.

Whereas both the attributional and decisional approach do not prescribe the allocation approach to be applied, the consequential approach is intimately linked to the avoided burden approach.

The environmental impacts related to the product or service under study differs too. The attributional and decisional approaches try to quantify the impacts caused by the product system supplying the average and extra consumption, respectively. The consequential approach tries to quantify induced impacts.

Tab. 1 Main characteristics of attributional, consequential and alternative consequential approach in life cycle inventory analysis

	attributional	consequential	decisional
purpose	reporting / decision support *	decision support	decision support
time	past or future	past or future	past or future
relations	economical and/or contractual	identified via general equilibrium models	economical and/or contractual
environmental impacts	caused by product system supplying avrg. consumption	induced by decision	caused by product system supplying extra consumption
multi-output processes and recycling	allocation or system expansion	avoided burden (system expansion)	allocation or system expansion
Main scientific contributions	Reinout Heijungs	Bo Weidema, Thomas Ekvall	Rolf Frischknecht

*: in today's practice, attributional LCA are often used for decision support

Advantages and disadvantages

In this section the advantages and disadvantages of the three approaches are described. Partly, arguments of experts have been reproduced without commenting them.

It shows, that consequential modelling is still highly debated but that in particular the promotors of the consequential approach disqualify the usefulness, appropriateness and feasibility of the attributional approach. The decisional approach got only little attention so far and hence only little third party opinions on its advantages and disadvantages are available yet.

Tab. 2 Advantages (+) and disadvantages (-) of the approaches

		attributional	consequential	decisional
LCI databases	+	Most currently available LCI databases are of an attributional nature.		
	-		Consequential LCI databases are still lacking.	Decisional LCI databases are still lacking.
Methodology / standardisation	+	The attributional LCA methodology is standardised in the ISO standards.		
	-	Despite standardisation, some contentious aspects remain (allocation, recycling)	No harmonised nor standardised methodology available yet. Different schools exist (consequential versus decisional approach).	No harmonised nor standardised methodology available yet. Different schools exist (consequential versus decisional approach).
Relevance in decision context	+	In some situations, an attributional LCA is a sufficiently accurate simplification of reality.	The consequential LCA is dedicated to decision making contexts.	The decisional LCA is dedicated to decision making contexts. It attributes environmental impacts according to contractual relations and thus shows the environmental consequences of a company's individual behaviour.
	-	Theoretically, decisions must not be based on attributional LCAs.	It is doubted whether LCA is the right instrument to assess macro-economic changes in market behaviour and environmental impacts	It is doubted whether contractual information is always adequate to identify changes in environmental impacts., in particular with regard to constrained markets (e.g. fully explored hydro power potential in Sweden or Switzerland).
Feasibility of modelling	+	Modeling average situations is rather straightforward. The results are rather stable in time.	Arguments from Weidema et al. (1999): After identifying the marginal (affected) technology, less data needs to be collected as compared to (average) technology mixes Uncertainty in particular technology's data is reduced as compared to average data. Marginal data are more stable (given no changes in boundary conditions such as economic constraints and long-term prices) as compared to average data	Forecasts based ontractual relations (with suppliers of an additional demand) are less contentious as compared to forecasts on changes in market situations due to a change in demand. Clear rules can be formulated to reduce the risk of position-oriented modeling.

		attributional	consequential	decisional
	-	Even though many LCA case studies rely on attributional modeling and data, some consequential/decisional aspects may be included. This may lead to inconsistencies or even distortions, particularly relevant in comparative assertions.	Due to changing economic situations with regard to affected marginal suppliers, LCI models may require periodic updates. The link between a usually small LCA functional unit and changes in macro-economic market situations is weak and sometimes even speculative. Opens opportunities to follow a position-oriented modeling (modeling guided by interest). Limitations, taken from (Ekvall 2002): Completeness: uncertain future and large LCA data gaps Accuracy: modeling of economic mechanisms still in its infancy Relevance: environmental responsibility may go beyond causal relationships; environmentally suboptimal may be supported; LCA results and conclusions may be considered unfair	Assumptions on the supplier of an additional unit of product are required with regard to spot market situations (e.g., London Metal Exchange, electricity market).
Acceptance / Communication	+	Decision makers are used to attributive modeling. The concept is easy to communicate and understand	The concept as such is rather easy to communicate.	The concept as such is rather easy to communicate.
	-	The limited validity of attributional LCAs in decision contexts may be ignored.	The results of particular LCA case studies may pose increased requirements on the communication. Some results and conclusions of case studies are hard to understand (e.g., an EPD of Swedish hydro power station should in fact consist of modeling Danish coal power as the marginal power source, (Weidema 2001)).	

Preliminary assessment

If the results of an LCA are supposed to be used for decision support, the concept of attributional LCA is of limited use. But before a consequential or decisional approach is adopted for environmental decision support, a basic discussion about and a clear idea on the role and capabilities of LCA is needed first.

From my point of view, the main question is whether (product) LCA is suited to assess the global effects on the environment of individual decisions (consequential approach, linking micro-economic actions to macro-economic (environmental) consequences) or rather a tool to efficiently allocate scarce environmental resources to individual products and services (attributional and decisional approach). The latter requires supporting measures, namely a (national or international) environmental policy that defines national or regional reduction targets for the emission of pollutants and the extraction of resources. The LCA currency "eco-points" then plays the role of money to facilitate efficient allocation of environmental resource.

On the level of environmental product declarations (EPDs) and LCA based and certified ecolabels, it makes little sense to base the underlying LCA on a consequential modelling. The attributional and decisional models guarantee that the current or planned emissions and resource consumptions of the supply chain are attributed to the labelled products.

On the level of regional or national policy support, consequential or decisional approaches may be more feasible and relevant. Questions like "what are the effects on the environment of increasing the share of heat pumps on total European heating systems to 10 %?" ask for a decisional or even consequential LCA approach.

In such cases, the forecast on the future development of markets is highly relevant: is the capital available to the energy industry used to replace and renew old, inefficient and polluting power plants (to cover a rather constant demand), or to install additional new power plants and to keep the old ones running (to cover additional demand). The market volume may even be shrinking and thus inefficient and expensive power plants (primarily in terms of running costs) are taken out of operation.

The goal of a policy-supporting LCA on electric heat pumps may be to identify the environmentally least polluting mean of electric power production to cover the additional demand and to compare it to other heat supply and energy saving scenarios that allow for a (environmentally) different development of the electricity sector.

LCAs on a product level will independently rely on current or future electricity supply contracts and helps to identify those applications, where green electricity

pays most. This is done within the macro-economic situation that develops under given international, regional and national policies.

Recommendations on behalf of the German network on life cycle inventory data

I recommend to establish LCI datasets primarily on the basis of the attributional and the decisional approach. The attributional approach is sensible for environmental reporting and product labelling and declaration. The decisional approach is sensible for product and process development, site and supplier evaluation.

There are relevant LCA applications, in particular with regard to national and European policy making, where limitations and interrelations on a macro-economic scale are highly relevant. Limited availability of biomass or limited hydro power potential need to be considered when it comes to an environmental assessment of large-scale policy measures.

LCI data should be supplied in a manner that allows to serve both purposes and thus both modelling approaches. In concrete terms this means either supply of two different datasets (attributional and decisional) per product or of one dataset only but on a level of detail that allows for goal-specific adaptations.

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