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Estimation of the size of error introduced into consequential models by using attributional background datasets

Bo P. Weidema [1]

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Abstract
Purpose A systematic comparison is made of attributional and consequential results for the same products using the same unit process database, thus isolating the effect of the two system models. An analysis of this nature has only recently been made possible due to the ecoinvent database version 3 providing an access to both unallocated and unlinked unit process datasets as well as both attributional and consequential models based on these datasets. The analysis is therefore limited to the system models provided by ecoinvent.
Methods For both system models, the analysis was made on the life cycle inventory analysis (LCIA) results as published by ecoinvent (692 impact categories from different methods, for 11,650 product/activity combinations). The comparison was made on the absolute difference relative to the smallest absolute value.
Results and discussion The comparison provides quantified results showing that the consequential modelling provides large differences in results when the unconstrained (marginal) suppliers have much more/less impact than the average, when analysing the by-products, and when analysing determining products from activities with important amounts of other coproducts.
Conclusions The analysis confirms that for consequential studies, attributional background datasets are not appropriate as a substitute for consequential background. The overall error will of course depend on the extent to which attributional modelling is used as part of the overall system model. While the identified causes of differences between the attributional and consequential models are of general nature, the identified sizes of the errors are specific to the way the two models are implemented in ecoinvent.

Keywords Attributional modelling · Comparison · Consequential modelling · Coproducts · Decision support · Marginal suppliers

1 Introduction and objective of analysis

In life cycle inventory (LCI) analysis, it is common to distinguish between the two fundamentally different modelling principles that have become known as attributional and consequential modelling. These terms were originally coined at an international workshop on electricity data for LCI in 2001 (Curran et al. 2005), where it was stated that attributional and consequential modelling responds to different types of questions:

- Attributional LCI aims to answer "how are environmentally things (pollutants, resources, and exchanges among processes) flowing within the chosen temporal window?" (Curran et al. 2005)
- Consequential LCI aims to answer "how will flows change in response to decisions?" (Curran et al. 2005)

The two modelling approaches have been defined in the glossary of the Shonan database guidelines (Sonnemann and Vigon 2011) as follows:

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✉ Bo P. Weidema
bweidema@plan.aau.dk

[1] Danish Centre for Environmental Assessment, Aalborg University, 9000 Aalborg, Denmark

- Attributional approach: system modelling approach in which the inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule.
- Consequential approach: system modelling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit.

While it is thus generally acknowledged that the two approaches have different purposes and give answers to different questions, it is not unusual to see attributional modelling or a mix of the two modelling approaches applied to studies with a consequential purpose, with results presented as a comparative or as an estimate of the effect of increasing or decreasing system output, which points to a lack of understanding among practitioners of the relation between application area and modelling in general (Andrae 2014; Plevin et al. 2014).

Before the advent of the ecoinvent database version 3 (Ecoinvent 2013) that provided a generally available consequential background database, the only practically available option for consequential LCIs was to use an attributional database in the background and changing the foreground processes—or those processes with the largest influence on the result—to consequential modelling. It is therefore of interest to investigate the size and extent of the errors introduced by this practice.

In this paper, the size and extent of the errors introduced by using attributional data in consequential studies are investigated by comparing the life cycle impact analysis (LCIA) results obtained with the two modelling approaches for the same products using the same unit processes from the same unit process database, thus isolating the effect of the two modelling approaches. An analysis of this nature has only recently been made possible due to the ecoinvent database version 3 providing an access to both unallocated and unlinked unit process datasets as well as both attributional and consequential models based on these datasets. The analysis is therefore limited to the system models provided by ecoinvent, and while the identified causes of differences between the attributional and consequential models are of general nature, the identified *sizes* of the errors are specific to the way the two models are implemented in ecoinvent, see Box 1 (Electronic Supplementary Material): "Summary of linking rules distinguishing attributional and consequential system models in ecoinvent", which summarizes the automatic database linking rules as provided in more detail in Chapter 14 of Weidema et al. (2013).

This paper is not intended to be a validation of or a statement on the correctness of the consequential modelling in the ecoinvent database, but exclusively to investigate the size and extent of the errors introduced by using attributional background datasets for consequential studies.

2 Methods

The analysis has been performed on two system models from the ecoinvent database version 3.1, published in 2014, namely the attributional system model "Allocation, ecoinvent default" and the consequential system model "Substitution, consequential, long-term". For both system models, the analysis was made on the LCIA results as published by ecoinvent for 692 impact categories from different LCIA methods and for the 11,650 available product/activity combinations.

Of the 11,650 products, 1345 product/activity combinations are found only in the attributional model, not in the consequential. These are by-products that in an attributional model appear with their allocated result in a separate dataset, while this is not the case in a consequential model where by-products are eliminated by substitution.

Of the 11,650 products, 318 product/activity combinations are found only in the consequential model, not in the attributional. These are the first of all conditional exchanges that represent induced changes in consumption related to constrained markets, which are not included in an attributional model. Furthermore, due to the incompleteness of the database, some wastes are not produced by any activity in the database while an activity providing treatment of this waste can still exist as a dataset in the consequential model. In the attributional model, such treatment activities are not included.

The remaining 9987 product/activity combinations were then compared, on the absolute difference relative to the smallest absolute value:

$$\mathrm{ABS}(A-C)/\mathrm{MIN}(\mathrm{ABS}(A), \mathrm{ABS}(C))$$

3 Results

Of the 9987 comparable product/activity combinations, 127 were excluded due to one or both of the values being zero, which occur when a dataset is empty or has no relevant exchanges for a specific LCIA method.

Out of the 127 excluded product/activity combinations, 29 only give zero result in the attributional model, which occurs when a multi-output dataset is empty except for the product outputs. The attributional LCIA result will be zero for all coproducts after allocation, while for the determining coproduct the consequential model will provide a result that includes the upstream displacements caused by the by-product output, and the dataset will therefore no longer be empty.

Four of the 127 excluded product/activity combinations only give zero results in the consequential model. This occurs for the not fully utilised by-products, Argon and Nitrogen, where the consequential market links to a burden-free reduction in release, while the attributional system performs allocation with the other inert gases.

For the 9860 remaining product/activity combinations, the most extreme differences of several orders of magnitude between the two system models are found for very specific impact categories, e.g. "EDIP: non-renewable resources, lanthanum", "ecological scarcity: pesticides to soil", "ReCiPe: ionising radiation".

To make the results more generally relevant, the following analysis exclude the specific LCI results, resource impact categories, and older LCIA methods (CML2001, EPS2000), bringing the total number of impact categories down from 692 to 401.

On an average in the 401 impact categories:

- 67% of the results have >10% difference
- 22% of the results have >100% difference
- 16% of the results have >200% difference
- 5% of the results have > order of magnitude difference

The differences are slightly smaller when limiting the comparison to the 11 total single-score categories, where:

- 56% of the results have >10% difference
- 13% of the results have >100% difference
- 9% of the results have >200% difference
- 3% of the results have > order of magnitude difference

This reduction in differences in the single-score categories is expected, since they aggregate a large number of small differences with opposite signs that counterbalance each other. Still, the amount and size of differences is noteworthy.

4 Discussion

When analysing the causes for the above differences between the attributional and consequential LCIA results for the same products, it was found that the causes can be grouped under five headings:

- Marginal suppliers very different from average
- Speciality products
- Multiple determining products
- By-products from treatment activities
- Determining products heavily influenced by by-products

In the following, each of these situations is described with an illustrative example taken directly from the ecoinvent database. The examples are not meant as examples of the best possible or most exhaustive modelling of each of the illustrated situations.

4.1 Marginal suppliers very different from average

Since the attributional model includes an average of all suppliers, while the consequential model only includes the marginal (unconstrained) suppliers, it is expected that large differences will result when the marginal suppliers have very different impacts than the average suppliers.

One of the more extreme examples of this is the data on land tenure, as illustrated in Fig. 1, where the consequential result is 100 times larger than the attributional. The output of the market for "land tenure, arable land" is on average supplied partly (1%) by intensification and clear-cutting with impacts of 0.069 Pt/unit of output and partly (99%) by land already in use with zero impacts. In the consequential model, "land already in use" is a constrained activity, not able to react to a change in demand, thus all the required output has to be supplied by the unconstrained "intensification and clear-cutting".

4.2 Speciality productions

A specialty production is an activity that is dependent on the input of a material for treatment, yet is not a treatment activity, i.e. the determining product of a speciality production is not a service of treatment for a material.

Products that are labelled based on a specified percentage of recycled material will always be speciality products, as in the example of "Graphic paper, 100% recycled" in Fig. 2. Upstream, the attributional modelling only includes the treatment activity, which is then—together with the speciality production itself—allocated by revenue together with the products of the waste paper providers, resulting in an impact of only 4 Pt/Mg recycled graphic paper. In the consequential model, an additional demand for the speciality product reduces the amount of the waste paper that goes to the marginal treatment activity for the material, here the production of recycled tissue paper. To keep the output of tissue paper constant, the reduced amount recycled tissue paper must be compensated by an increase in the virgin tissue paper production. The net impact of the reduced supply of waste paper to the tissue industry is 111 Pt/Mg, which together with the 51 Pt/Mg from the speciality production itself leads to an overall impact of 162 Pt/Mg recycled graphic paper (compared to the 4 Pt/Mg in the attributional model). Note that in the consequential model, an additional demand for a fully utilised recycled material does not change the overall amount of material recycling but only the relative proportions of recycled material in different products (here, more in graphic paper, less in tissue).

4.3 Multiple determining products

As a general rule for joint production, there will be a maximum of one determining coproduct from each coproducing

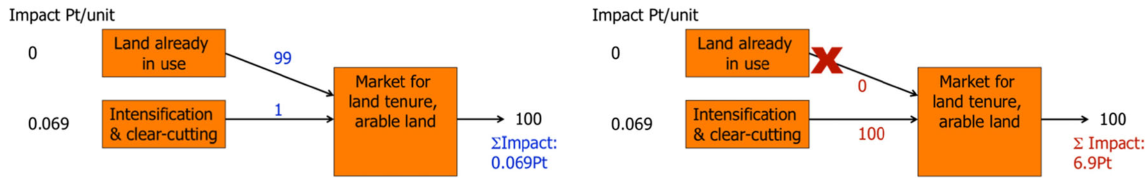


Fig. 1 LCIA results for the attributional (*left*) and consequential (*right*) models for the output of the market for "land tenure, arable land". Data from the "ReCiPe Endpoint (E, A):total:total" method

unit process. But a special situation arises when more than one joint product from the unit process have no alternative production routes, in which case, all of these joint products will be separately determining. In this situation, the prices of the joint products will adjust until all the joint products have the same normalised market trend, since only then their markets will be cleared (Weidema et al. 2009). In this situation, a change in demand for one of the joint products will influence the production volume of the joint production in proportion to its share in the gross revenue of the joint production. This is equivalent to the result of an economic partitioning (allocation) of the coproducing process. Furthermore, a consumption adjustment will take place via constrained markets for the joint products, in order to maintain a balance in supply and demand (and thus in mass balances, which is otherwise lost in economic partitioning).

In the ecoinvent database version 3.1, there is only one situation of multiple determining products, namely rare earth oxides production. Here, we describe the modelling for one of these products, namely lanthanum oxide. A more detailed description of the modelling of the entire dataset in ecoinvent can be found on the website consequential-lca.org (Consequential-LCA 2015).

A demand for 1 kg lanthanum oxide on the market is met by a 1 kg increase in supply in both the attributional and the consequential model. However, as shown in Fig. 3, the attributional model provides this supply exclusively from an allocated part of the coproducing activity, while the consequential model takes into account that the revenue provided by the demand for lanthanum oxide alone is only able to stimulate a change in output from the rare earth oxides production of 0.352 kg, namely the amount that corresponds to the revenue from 1 kg lanthanum oxide relative to the total revenue from all the determining products. The remaining supply (0.648 kg) must therefore come from a reduction in consumption by the marginal consumers of lanthanum oxide. At the same time, the stimulated increase in output of 0.352 kg lanthanum oxide implies a corresponding increase in the other rare earth oxides (Neodymium, Cerium, etc.). Clearing the markets for these products require a corresponding increase in consumption of these rare earth oxides of 0.897 kg. The inclusion of these consumption adjustments obviously leads to the impacts from the consequential model to be very different from the attributional.

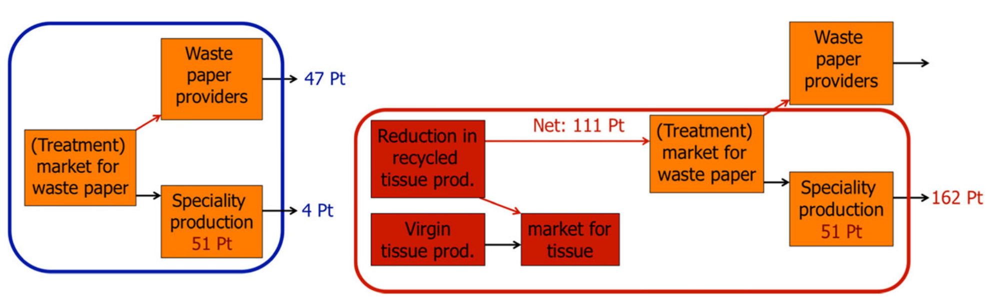
It may be argued that the modelling of rare earth production as having multiple determining products is only necessary because of the rather crude modelling of this activity in ecoinvent, and that a more detailed analysis may show that only one (or fewer) of the products is really determining. However, even if this is the only example of this situation in ecoinvent version 3.1, the principle of the modelling is also relevant in other situations, e.g. the meat coproducts of an abattoir (Consequential-LCA 2015), for which data are not available in ecoinvent version 3.1.

4.4 By-products from treatment activities

When comparing outputs of treatment markets, where the output is the treatment of a by-product, the attributional model only includes the emissions from the treatment activity while the consequential model includes the upstream activities displaced by the by-products.

In Fig. 4, the attributional treatment market for a rape meal (a by-product from operation of a rape oil mill) only has inputs of transport with impacts amounting to 0.35 Pt/Mg of rape meal. In the consequential model, the displaced protein from

Fig. 2 LCIA results for the attributional (*left*) and consequential (*right*) models supplying an output of the speciality product "Graphic paper, 100% recycled". Values are per megagram paper from the ReCiPe Endpoint (H, A) method



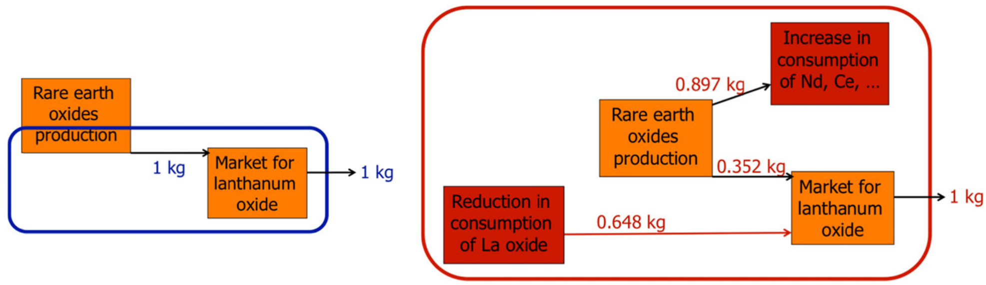


Fig. 3 The attributional (*left*) and consequential (*right*) models for the output "Lanthanum oxide" from rare earth oxides production

soy meal is included, giving a negative (avoided) impact of 140 Pt/Mg rape meal.

However, this comparison is only included because both product systems supply "treatment of 1 kg rape meal" and thus appear as the same product/activity combination in the two ecoinvent system models. But in reality, the comparison is not really meaningful because the two product systems do not play the same role: the consequential result shows the consequences of changing the demand for 1 Mg of rape meal, while the attributional result shows the average treatment required to bring 1 Mg of rape meal to the market.

In these cases, rather than comparing the treatment activities (here, "treatment of 1 kg rape meal"), a more reasonable comparison would be between the allocated outputs of the attributional system (here, rape oil and protein) and their consequential counterparts. Nevertheless, these comparisons still show a noteworthy difference between the two system models: 109 vs. 78 Pt/Mg rape oil and 107 vs. 140 Pt/Mg protein for the attributional and consequential impacts, respectively.

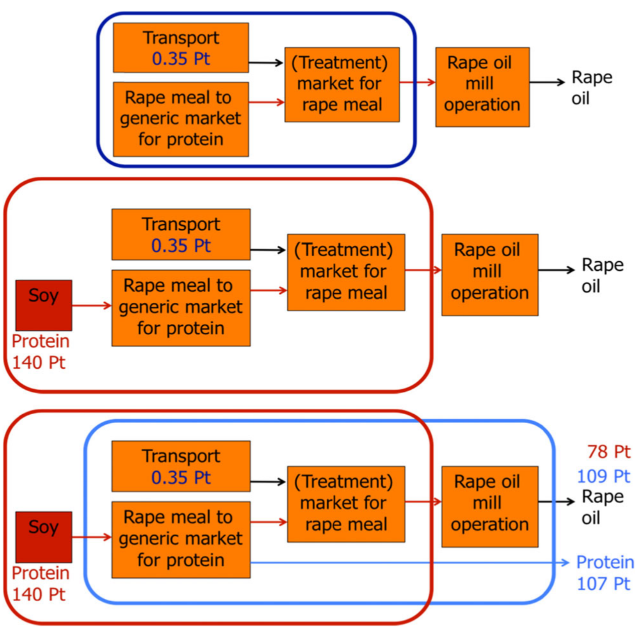


Fig. 4 The attributional (*upper drawing*) and consequential (*middle drawing*) models for the output from the (*treatment*) market for a rape meal, and a comparison (*lower drawing*) of the LCIA results of a rape oil and protein in the two models. Values are per megagram rape meal using the ReCiPe Endpoint (H, A) method

4.5 Determining products heavily influenced by by-products

Large differences between consequential and attributional LCIA results may also occur for determining products that are produced together with by-products that displace very polluting or very clean activities compared to the burden that is allocated away from the determining product in the attributional model.

One of the more extreme examples of this is silicon tetrahydride; here, analysed with the ReCiPe Endpoint (E, A) method: the upper part of Fig. 5 shows the attributional result where the majority of the impact is allocated to the relatively valuable by-product silicon tetrachloride, leaving only 11 Pt/kg to the silicon tetrahydride. This allocation also results in only 0.5 kg of silicon input to produce the output of 1 kg silicon tetrahydride. The stoichiometric requirement for the silicon hydrochloration activity is 17.2 kg silicon, as shown in the consequential model (lower part of Fig. 5), which arrives at an impact of 378 Pt/kg silicon tetrahydride, composed of 390 Pt/kg for the sum of all inputs and −12 Pt/kg from the avoided production of silicon tetrachloride. The extreme difference in the results is here caused by the low impact

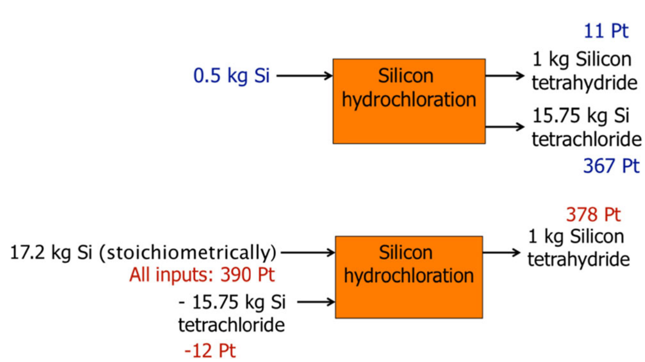


Fig. 5 LCIA results for the attributional (*upper drawing*) and consequential (*lower drawing*) models for the supply of silicon tetrahydride, using the ReCiPe Endpoint (E, A) method

of the marginal production route for the silicon tetrachloride combined with its relatively high value.

5 Conclusions

The comparison between the attributional and consequential LCIA results, for the same products using the same unit process database, isolates the effect of the two modelling approaches. The differences in results are large: for the 401 impact categories and 9860 product/activity combinations analysed, 67% of the results show more than 10% difference, and for 5% of the results the differences are above an order of magnitude.

Although some of the more extreme differences may be due to errors in the database and unreasonable comparisons of product/activity combinations for by-products for treatment with the same names with the same but with very different functions (as demonstrated with the rape meal example), the high frequency of differences above 10% confirms that the use of attributional models for consequential purposes, or vice versa, will imply important errors. The overall error will of course depend on the extent to which attributional modelling is used as part of the overall system model.

The analysis confirms that attributional background datasets are not appropriate as a substitute for consequential background data, especially in situations when:

- The unconstrained (marginal) suppliers have much more/less impact than the average,
- Analysing the use of by-products, especially from treatment activities, for speciality products and from activities with more than one determining product,
- Analysing determining products from activities with important amounts of other coproducts.

The full consequential model supplied with the ecoinvent background database thus removes what has hitherto been an important source of error for consequential results, besides saving LCA practitioners a lot of time-consuming modelling.

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