Market aspects in product life cycle inventory methodology

Bo Pedersen Weidema

I. Krüger AS, Gladsaxevej 363, DK-2860 Soeborg, Denmark

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In planning a product life cycle inventory analysis, the correct choice of methodology often depends on market information. This paper discusses a number of points in the life cycle inventory methodology (choice of product alternatives, geographical system boundaries, technological levels and co-product allocation rules) where the market aspect becomes obvious and where a disregard for these aspects may lead to serious flaws in the results.

Keywords: life cycle inventory; methodology; market information

Introduction

A product life cycle assessment is a systematic inventory and comprehensive assessment of the environmental effects of two or more alternative activities relating to a defined product in a defined space and time, including all steps and co-products in its life cycle. A complete life cycle assessment consists of several interrelated components (see *Figure 1*). It should be noted that the procedure suggested by these points will often be made iteratively in practice.

Recently, a number of papers have been published on the subject of manuals and methodology for product life cycle assessment dealing primarily with the inventory phase[1–5]. None of these papers adequately reflects the importance that market aspects and the economic disciplines may have in life cycle inventory methodology.

In contrast to other kinds of environmental assessments, which are oriented towards more site-specific processes (waste minimization assessments and other technical assessments) or enterprises (environmental reviews), life cycle assessments are centred on products. This already signals its market aspects, since products are generally market defined and market driven.

This paper discusses a number of points in the life cycle inventory methodology where the market aspect becomes obvious and where a disregard for this aspect may lead to serious flaws in the results.

I. **Planning** (*goal definition and scoping*)
Objectives
Definition of product and choice of alternatives
System borders (space, time, product chain)
Choice of environmental parameters
Choice of method for aggregation and evaluation
Strategy for data collection

II. **Screening**
A preliminary execution of phases III–VI
Adjustment of plan

III. **Data collection and data treatment** (*inventory analysis*)
Measurements
Interviews
Search in literature and handbooks
Theoretical calculations
Search in databases
Qualified guessing
Data qualification
Sensitivity analysis
Data addition

IV. **Evaluation** (*impact assessment*)
Data aggregation
Normalization of data in relation to a specified reference
Valuation of data in relation to a specified set of values

V. **Adjustment of alternatives** (*improvement assessment*)

VI. **Possible reiteration of phases** III–V

Figure 1 The phases in executing a product life cycle assessment. The terms in parentheses refer to the so-called SETAC terminology coined by Fava *et al.*[17] and adjusted by Consoli *et al.*[4]

Product definition and product alternatives

A central part of the goal definition of a life cycle assessment is the precise description of the product and the alternatives to be investigated and compared.

The product can be described either as a physical product, e.g. a washing machine, or as a service, e.g. laundry. In both cases it is important to specify what minimum quality the product must meet. For example, it is not enough to refer to a laundry product as being 'clean clothes'. The degree of cleanliness should be specified (e.g. by the light reflection of the clothes), as well as how dry the clothes should be (e.g. maximum

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48% humidity), and where and how fast the clothes are delivered (e.g. to the owner's home address within 24 h). All these quality specifications place demands on processes and materials in the life cycle of the product, and therefore have an impact on the total environmental effect of the product system.

It is a reasonable demand that the products should at least fulfil their advertised claims[6], and that they should also fulfil existing product standards according to law or common trade agreements. Griesshammer *et al.*[7] mention examples of misleading product names (indicating the bleaching properties of detergents), which may lead the consumer to expect quality other than the actual quality, and which may even lead investigators to assign the product to a wrong product group.

The product must be defined not only by its inherent quality, but also in relation to its actual use, e.g. as an energy service[8,9]. This is often termed 'the functional unit of product'. For products for immediate consumption this is relatively easy to define. However, in the energy studies reviewed by Fritsche *et al.*[9] the functional units of 'energy services' are only used in a few studies. Griesshammer *et al.*[7] conclude that very often the product unit is not correctly chosen, and that it may often be severely influenced at the household level, e.g. by individual consumer behaviour[10]. For durable products the determination may be even more difficult, since the definition will be influenced by factors such as durability, frequency of use and ease of repair[7].

Quality specifications also delimit what alternatives can be included in the investigation, since it is indirectly a specification of what can be regarded as similar products. For example, it may be acceptable to compare two laundries, even though they have different speeds of delivery, while it may be unacceptable to compare the two laundries if they do not deliver equally clean clothes. Very heavy demands on the quality may mean that no alternatives are left. In the end it is the customer who decides what can be regarded as comparable products. But it may well be that the customer can be influenced by information about the environmental effects of the alternatives, e.g. if it was made clear that the not-so-white clothes were the result of using environmentally friendly detergents and that the not-so-quick delivery was due to the laundry being delivered by bike. Therefore, it is important to consider which quality demands are indispensable and which might be departed from. Standard methods to identify and classify what can be regarded as comparable products have not yet been developed. Such methods would necessarily involve some kind of consumer preference information.

It is possible to imagine alternatives for each step in the life cycle of a product. Alternatives can be found at different levels:

- different processes or material compositions involved in the production of the same product (e.g. the same washing machine);
- different, but comparable products (e.g. two different washing machines);
- completely different products fulfilling the same need (e.g. a household washing machine compared to a laundry service or washing by hand).

The number and level of alternatives that should be included in the investigation are subject to the purpose of the investigation. Öko-institut[11] suggests that a zero-alternative should also be investigated, i.e. what would happen if the product were not produced at all. In their study on methodology for environmental labelling, Dall and Toft[12] suggest a division into ideal comparisons (that include all alternative ways of performing a function, e.g. for wrist watches energy may come from both batteries, manual winding, shaking and solar cells), and more pragmatic comparisons based on the market performance of the different alternatives, which should reflect the consumer perception of the alternatives. The pragmatic approach may lead to the recommendation of products that are not environmentally the best alternative, and Dall and Toft therefore suggest that under these circumstances the environmental label should be accompanied by information on the compromise made. This could be done by a reference to the better alternative, for example.

A thorough analysis will search for alternatives to all raw materials and all processes. Obviously, in any practical study limitations have to be imposed, but if the selection of alternatives is too haphazard, or if some alternatives are disregarded without reasonable arguments, this will inevitably lead to criticism. This has been the case with the German environmental label, which has been criticized, for example, for excluding roll-on deodorants as an alternative to CFC-free aerosol deodorants, and for excluding water-based paints as an alternative to solvent-based paints[13].

Geographical system boundaries

Production facilities and the effects of their environmental releases depend strongly on local conditions. Therefore, an essential part of the system description for a life cycle inventory is the description of the geographical areas that are included in the investigation and how their boundaries are designated. Within the overall prerequisite that the geographical areas included should give an equal representation of all product alternatives, an investigation may be based on:

1. the actual geographical location of specific enterprises in the life cycle of the products;
2. averages for a geographical area (from local to global) representing the actual supply situation (relevant for generic studies and for specific studies where the producer has several alternative suppliers and outlets or where it is not possible to identify the specific supplier or customer, as, for example, in an electricity network);

3. the geographical location of the marginal production, i.e. the production facility that would be taken into use or out of use when the demand respectively increases or decreases as the result of implementation of the life cycle assessment (relevant for generic studies and for specific studies where changes in the amount of raw materials, energy or products do not affect the environment at the specific supplier or outlet but are referred on to a marginal production facility);
4. the worst geographical location (relevant for studies that focus on short-term improvement options);
5. the best available or best possible geographical location (relevant for studies where the objective is product improvement or development).

As can be seen, the choice of method depends to some extent on the objectives of the study. Furthermore, each method has its advantages and disadvantages. While giving a very precise picture, the study of specific enterprises demands a lot of field work and excludes the use of statistical information and databases. Average values may fluctuate quite heavily over time and correct averages can be quite complicated to obtain unless statistical information is available. However, most of the readily available data in databases, handbooks and information from experts and trade organizations will be average data in one form or another.

It can be argued that the use of environmental data on the marginal production reflects most correctly the actual environmental impact of implementing the result of the life cycle assessment. However, identification of the marginal production may be time-consuming and will often demand information from industrial experts or market researchers. On the other hand, once identified, the data collection effort is limited and the marginal production will often be more stable over time than the average production. Also, the identification of the worst or best geographical location will depend on information from experts.

Temporal system boundaries: the level of technology

Technology develops with time and often becomes more environmentally benign. As in the case of geographical system boundaries, the result of the investigation may be misleading if different technological levels are chosen for the different alternatives to be compared, as has been pointed out by Fritsche *et al.*[9] in their review of energy analyses where old and new facilities are often compared. Likewise, Griesshammer *et al.*[7] mention examples of new concepts being judged on the basis of newly introduced products from small companies and compared to old established products from large companies.

The chosen technological level should give an equal representation of all product alternatives. Within this limitation, several technological levels can be distinguished, as detailed below.

Worst technology will give the largest environmental improvement if it is taken out of use. It may therefore be relevant to use worst technology as a basis for comparison if the purpose is to obtain the largest possible immediate environmental improvement, i.e. if the investigation has a short time horizon.

Average technology is often the easiest technology to obtain information on from statistics and handbooks. However, since such figures are often 5 – 10 years old, it may in fact be the worst technology that one obtains information on in this way. A reasonable picture of the average technology can only be obtained by use of new information. Average technology as a basis for comparison may give a reasonable picture of the effects on the environment on a short to medium range in sectors where no significant new investment can be expected.

Modern technology is the technology that most enterprises install today by new investments or renovations, also known as BATNEEC (best available technology not entailing excessive costs). It can be difficult to obtain accurate information on the actual environmental effects, since the technology has not been tested for longer periods. It will be relevant to use modern technology as a basis for comparison if the purpose of the investigation is, for example, to guide an enterprise when making new investments.

Best available technology is suitable for use as a basis for comparison if the investigation has a slightly longer time horizon or is directed towards particularly environmentally conscious enterprises or consumers. It may even be relevant to use:

Best technically possible technology, which is not yet installed anywhere, but for which the environmental effects can be calculated.

Marginal technology is taken into use or taken out of use if the produced amounts are increased or reduced, respectively. It is not always the worst technology that is taken out of use nor modern technology that is taken into use. This is, among other reasons, due to geographical, technical, political or economic limitations in the availability of modern technology. To use marginal technology as a basis for comparison thus implies the use of either the worst, the average or modern technology, depending on which of these will actually be affected by the changes in the produced amounts. Therefore, marginal technology can give the most correct description of the actual consequences for the environment. However, in a given situation it may be difficult to establish what is actually the marginal technology, since this will depend on the above-mentioned particular geographical, technical, political and economic conditions.

Fluctuations in raw material source

Some product systems may change the nature or source of their raw material(s) regularly owing to changes in supply and demand, and thus in market prices. A similar condition applies to the source and type of energy used in a product system. Thus, when reporting a raw material that is substitutable it should be listed both in its generic form (allowing substitution between the different subsystems) and expressed as an average mixture, indicating the range and distribution of the variation. Such precision in reporting has not been common in the life cycle assessments published to date (as reviewed by Pedersen and Christiansen[14]).

Co-product allocation

A process often renders more than one product with a positive economic value (an obvious example is a co-generation plant that produces both electricity and district heating). Such products are called co-products. A co-product that is used in the next step of the investigation is called a main product. Co-products that are used for other purposes (outside the scope of the investigation) are called by-products. Thus, what is a main product and what is a by-product depends on the aim of the investigation (note that some authors, for example Vigon *et al.*[5], use the term co-product for by-products only). It would not be fair to make the main product solely responsible for all environmental effects from the process and the preceding steps in the life cycle (the accumulated environmental effect of the process). Thus, it is necessary to decide how this accumulated effect is to be allocated on the main and by-products of the process.

Most (by-)products can replace (substitute) one or more other products (for example, district heating can replace central heating with oil). If this happens, the production of these other products will no longer be needed, and the environmental effects that would otherwise come from this production will cease. One may say that this environmental effect has been avoided. Following this logic, the environmental effect to be allocated to the main product can be calculated as the accumulated environmental effect of the process minus the avoided environmental effect from the by-products (the accumulated environmental effect from the production of the replaced products). Following the same logic, the environmental effects of any intermediate processing of the by-product before it can replace another product should be allocated to the main product. If the replaced products have relatively large environmental effects, the environmental effect allocated to the main product may become negative. This allocation method has been used especially for allocation of benefits from waste incineration[5,15], and has been suggested as a general method by Pedersen[16]. For post-consumer open-loop recycling, Vigon *et al.*[5] suggest different modifications of this method in which either the environmental effects of the intermediate processing are allocated to the by-product, or the avoided effects and the effects of intermediate processing as well as the benefits from reduced waste handling are allocated between the co-products in some arbitrary proportion. The arguments for these suggestions are not clear, but Vigon *et al.* discuss the advantages and disadvantages of each of their proposed methods.

Obviously, the use of avoided effects cannot be used if the by-product does not replace another product. Furthermore, the method may be too complicated for some purposes, since it involves the addition of a new 'branch' to the process tree for every by-product, i.e. data on the environmental effects from the production of the replaced products. Another complication is that it may be quite time-consuming to establish with certainty which products are actually replaced, and this may vary over time. This will often demand information from industrial experts or market researchers and has much in common with the procedures for identifying marginal productions, whether geographical or technological (see above). However, other methods have similar complications, as will become obvious from the following discussion.

Most analysts dodge the issue completely or deal with it in an incomplete way, for example by assigning all effects to either the by-product or the main product or an arbitrary relation between these[8,17].

Some studies have divided the effects between the co-products according to their weight[18] and this has also been suggested as the general procedure by Consoli *et al.*[4] and Vigon *et al.*[5], although the latter authors apply a number of exceptions, as mentioned above and below. Other authors have suggested the use of the energy content of the products[19] or chemical equivalents. These suggestions keep the allocation connected to some physical property of the processes or products with the aim of keeping the allocation stable under a given technology[3]. However, such physical allocation methods have their limitations, for example:

- allocation by mass (weight) cannot be applied for energy services as, for example, the output from a co-generation plant;
- allocation by chemical equivalents may be useful for processes in the chemical industry, but cannot be applied, for example, to agricultural products;
- allocation by energy equivalents may be useful for products in the petrochemical industry where many by-products are used as fuel, but cannot reasonably be applied, for example, to metals.

Thus, Boustead[3] and Vigon *et al.*[5] give several examples of how different physical properties may have to be selected, to reflect the actual characteristics of the process or products. Even for the same process, different properties may have to be combined, as for electrolysis of water, where the environmental effects of the water supply should be allocated on a mass basis and the environmental effects of the electricity supply allocated on a molar basis (see ref. 5, p. 57).

Nevertheless, the use of physical properties does not necessarily give a fair allocation, as can be illustrated by three inconsistencies, as detailed below.

1. The physical properties of the processes may change

with fluctuating output distribution depending on the demand for the products (e.g. cracking products or the efficiency of a co-generation plant) thus again relating the allocation to market conditions.

2. The output of a process is divided into those with an economic value (co-products) and those without or with a negative economic value (waste). Since this division is purely economic, the same output may at times be regarded as a waste and at other times as a co-product, even though no technical changes have been made. A consistent use of physical properties for allocation would therefore be to allocate effects between both co-products and waste. However, most authors find this unacceptable and thus allocate effects only between co-products, although Vigon *et al.*[5] suggest that the allocation should be between all outputs that are utilized in other processes with economic output, irrespective of the value of the output itself. The problem is especially obvious when the main product is of low weight and relatively valuable compared to a heavy by-product with a very small value (e.g. a valuable mineral that is in low concentrations in the ore, and a low value overburden that may be used as construction material). In such cases the valuable main product (which may be the only reason for operating the process) will carry only a very small fraction of the environmental effects, which is clearly not fair. A further complication arises for marginal by-products which are sometimes utilized and sometimes dumped as waste. Vigon *et al.* suggest, in such cases, to allocate the full environmental effects to the main product. However, one would then have to decide when a by-product can be regarded as marginal and when it should carry its full share of the effects. Whatever definition is chosen, border-line cases will still occur.
3. The problem is further illustrated by other situations where the by-product is less valuable than the main product. In comparing a traditional process with an improved process that uses material and energy more efficiently and thus produces more of the main product and less of the by-product, the main product will carry more of the accumulated environmental effects than in the less efficient process. This is counter to the widespread notion that the efficient process is the more environmentally friendly.

From the above discussion, it seems obvious that allocation by physical properties works well when there is a close correlation between the chosen physical property and the value of the co-products. When this correlation is not close, the allocation becomes unfair, in extreme cases so unfair that it becomes obvious. The advantage of allocation by physical properties—its ability to give consistent results—may thus be offset by these results being consistently wrong.

The logical conclusion from this finding would therefore be to allocate the effects according to the economic value of the by-products. The value of the products is the obvious reason for maintaining the production and thus the environmental effects. This approach was apparently first used by Basler and Hofman[20] and has been suggested as a general methodology by Heijungs *et al.*[1] and by other authors, mainly in connection with the allocation of recycling benefits. The suggestion of Vigon *et al.*[5] to allocate household processes (e.g. a shopping trip) according to the purpose of the process follows the same logic.

The main complication in using economic values for allocation is their transient nature. Even when using prices averaged over longer periods of time, fluctuations are unavoidable. If prices change significantly, the life cycle inventory will have to be recalculated. The obvious advantage of the method is that it is universally applicable.

In fact, allocation by physical properties can be seen as a special case of allocation by economic value, applicable when the physical property in question exists for all the co-products to be allocated and is relatively closely correlated to the economic value of the co-products.

Based on the above discussion, the following standard procedure is proposed. For processes with more than one economic output, some of which leave the product system as by-products (raw materials for other product systems), the by-products should carry a part of the accumulated environmental effects of the process, to be calculated as either:

(a) the environmental effect avoided as the by-products replace other products (the accumulated environmental effect of producing the replaced products) when such a replacement takes place;
(b) a part of the accumulated environmental effects in proportion to the relative economic value of the co-products;
(c) a part of the accumulated environmental effects in proportion to the distribution of one or more physical properties among the co-products (e.g. weight, energy content, chemical equivalents).

The allocation method should be stated for the entire product system or for each multi-output process. The accumulated environmental effect and the values used for allocation should be given for each multi-output process. When using economic values (method (b)) it should be documented that the by-product does not substitute other by-products or, if so, that a sensitivity analysis shows that the use of economic values does not significantly influence the result compared to the use of avoided environmental effects (method (a)). When using physical properties (method (c)) the correlation between the physical property/properties in question and the economic value of the co-products should be documented.

Conclusion

In planning a product life cycle inventory analysis, the correct choice of product, product alternatives, geographical system boundaries, technological levels and co-product allocation often depend on market information. A purely technical approach may give misleading results. Thus, an interdisciplinary approach is called for, where technical experts, market experts and economists join forces to provide an inventory that reflects, to the largest extent possible, the actual consequences of implementing the results of the investigation.

Further research is recommended on the market aspects of life cycle assessment methodology and the actual importance of different methodological choices.

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