LCA Methodology

System Boundaries and Input Data in Consequential Life Cycle Inventory Analysis

Tomas Ekvall[1]* and Bo P. Weidema[2]

[1] Energy Systems Technology Division, Chalmers University of Technology, SE-412 96 Göteborg, Sweden
[2] 2.-0 LCA consultants, Amagertorv 3, 2., DK-1160 København K, Denmark

* **Corresponding author** (tomas.ekvall@me.chalmers.se)

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Abstract

Goal, Scope and Background. A consequential life cycle assessment (LCA) is designed to generate information on the consequences of decisions. This paper includes a comprehensive presentation of the consequential approach to system boundaries, allocation and data selection. It is based on a text produced within the SETAC-Europe working group on scenarios in LCA. For most of the methodological problems, we describe ideal methodological solutions as well as simplifications intended to make the method feasible in practice.

Method. We compile, summarize and refine descriptions of consequential methodology elements that have been presented in separate papers, in addition to methodological elements and general conclusions that have not previously been published.

Results and Conclusions. A consequential LCA ideally includes activities within and outside the life cycle that are affected by a change within the life cycle of the product under investigation. In many cases this implies the use of marginal data and that allocation is typically avoided through system expansion. The model resulting from a consequential life cycle inventory (LCI) also includes the alternative use of constrained production factors as well as the marginal supply and demand on affected markets. As a result, the consequential LCI model does not resemble the traditional LCI model, where the main material flows are described from raw material extraction to waste management. Instead, it is a model of causal relationships originating at the decision at hand or the decision-maker that the LCI is intended to inform.

Keywords: Allocation; consequential life cycle inventory analysis; input data; methodology; modelling; system boundaries

1 Introduction

1.1 Background

The life cycle model developed in a life cycle inventory analysis (LCI) should be an appropriate description of the relevant parts of the technological system. What parts are relevant depends on the aim of the study. The consequential LCI methodology described in this paper aims at describing how the environmentally relevant physical flows to and from the technological system will change in response to possible changes in the life cycle. We distinguish it from attributional LCI methodology, which aims at describing the environmentally relevant physical flows to and from a life cycle and its subsystems. A consequential LCI methodology is designed to generate information on the consequences of actions. Textbooks on decision theory (e.g., Grubbström 1977) are based on the recognition that such information is necessary to make a rational decision.

Several authors have previously made similar distinctions between the two types of life cycle assessment (LCA) methodology, although almost every author employs different terms to denote them (Heintz & Baisnée 1992, Weidema 1993, Baumann 1996, Frischknecht 1997, Heijungs 1997, Baumann 1998, Cowell 1998, Hofstetter 1998, Ekvall 1999a, Tillman 2000). The attributional/consequential terminology was adopted in 2001 at a workshop on LCI electricity data in Cincinnati (Curran et al. 2001), although the term attributional had already been in use for several years.

Consequential LCI methodology can be used in most LCA applications (Ekvall 1999a). A consequential LCI is likely to result in more comprehensive and accurate information about the consequences of buying a product, but at this point in time it may still be difficult to reach consensus on its detailed application in specific situations, especially for environmental labeling. Hence, it is an important task for LCA researchers to develop explicit procedural guidelines for the consequential methodology. This paper is part of that research, focusing on the modelling of indirect effects.

Most previous authors mention that consequential methodology implies that allocation is avoided by means of system expansion, because multifunctional processes and open-loop recycling affect processes outside the life cycle originally investigated. They also state that marginal data are to be used where relevant to describe the consequence of a decision. Consequential approaches to allocation problems are presented by, for example, Azapagic (1996), Azapagic & Clift (1999), Weidema (2000), Ekvall (2000b), and Ekvall & Finnveden (2001). A procedure for identifying marginal data is described by Weidema et al. (1999). Additional aspects of consequential methodology are described in a PhD thesis (Ekvall 1999a). The developments are summarized in recent reports (Weidema 2003, Weidema et al. 2004).

1.2 Aim and content of the paper

The purpose of this paper is to give a concise but comprehensive presentation of the consequential approach to system delimitation, allocation and data selection. It is based on a chapter in the SETAC-Europe working group report on scenarios in LCA (Weidema et al. 2004). We compile methodological elements from various sources in a presentation of how to decide what parts of the technological system should be included in a description of the effects of decisions on environmentally relevant physical flows and what type of data should be used to model these parts of the technological system. For most of the methodological problems, we formulate what we consider to be the ideal methodological solution in terms of relevance and accuracy. We also present simplifications intended to make the methods feasible in practice.

Sections 2–5 in this paper deal with different system boundary issues in the LCI. Section 6 deals with the question of what product should be supplied by unit processes in the expanded system. Section 7 presents a procedure for the identification of the marginal technology for the parts of the system that are only marginally affected by changes in the life cycle under investigation. Section 8 touches briefly upon the problem of future technological development. Finally, Section 9 presents some general conclusions.

2 Allocation for Multifunctional Processes

The allocation problems related to multifunctional processes are fairly well known. They have been extensively discussed in, e.g., the former working group on Inventory Enhancement within the European branch of Society for Environmental Toxicology and Chemistry (SETAC) and in the international organisation for standardisation (ISO). Although a compromise has been reached (ISO 1998), it has been criticized for its failure to take sufficient account of the fact that different approaches to the allocation problem are relevant to different situations (e.g., Ekvall & Tillman 1997, Baumann 1998). It also fails to deal explicitly with all aspects of the methodological problems involved. Hence, there may be a need to refine the methodology, both through adjustments of the current description in the ISO standard and by means of the formulation of additional recommendations.

The discussion and recommendations presented here are valid for consequential LCI methodology, i.e., for modelling the consequences of possible actions. They are based, to a large extent, on previous publications by Weidema (2000) and Ekvall & Finnveden (2001). We distinguish between allocation for multifunctional processes and allocation for open-loop recycling, because different methodological descriptions apply to these two cases (Ekvall 1999a).

Fig. 1 illustrates a simple, theoretical multifunctional process with two products. Only product A is used in the life cycle investigated; it provides an internally used function. Product B provides an external function, i.e., a function that is utilized in another system.

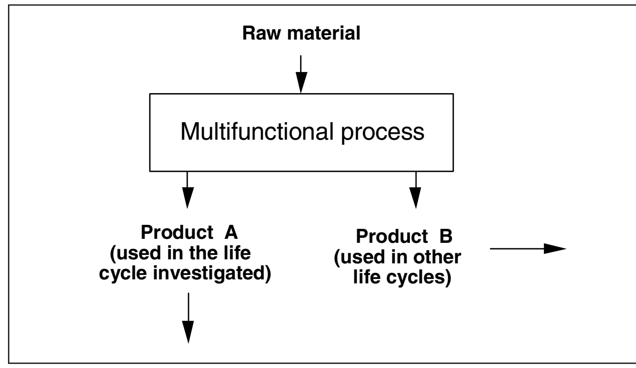

Fig. 1: Illustration of a theoretical multifunctional process

When the allocation problem can be expected to be insignificant for the conclusions of the study – e.g., based on experience from previous studies or because possible actions have little effect on the demand for Product A in the system investigated – the most easily applicable allocation approach can be used. What approach is the easiest to apply depends on, for example, what data have been collected for the multifunctional process.

When the allocation problem can affect the conclusions of the LCA, the adequate approach to the allocation problem depends on how the process reacts to a change in the use of product A in the life cycle under study. We distinguish between three different, theoretical types of multifunctional processes that call for different, consequential approaches to the allocation problem:

1. Products A and B are produced independently
2. Production of product B depends on the demand for product A.
3. Production of product A depends on the demand for product B.

In the first case, possible actions can have a significant effect on the production of product A, but little effect on the production of product B, because both products are independently produced. Examples are batch production of different products in a single production plant, and many service products. Our methodological recommendation is to divide the multifunctional process into single-functional subprocesses, if such exists (**Fig. 2**). Otherwise, allocation of the raw material demand, emissions and waste from the

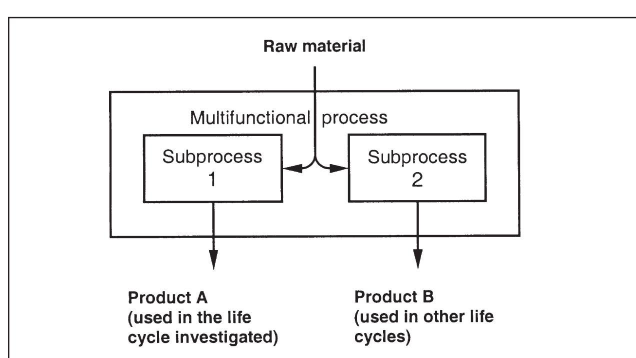

Fig. 2: Illustration of a theoretical multifunctional process that consists of two single-functional sub-processes

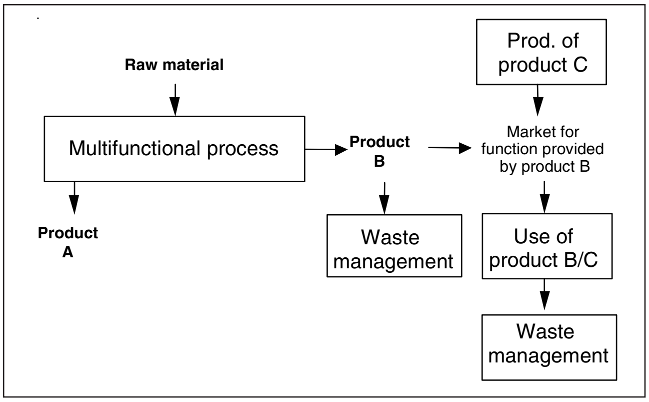

Fig. 3: Illustration of a theoretical multifunctional process and of the activities that may be indirectly affected by a change in the production of product B

multifunctional process should be based on physical, causal relationships within the multifunctional process (as described in ISO 1998), or an approximation of these approaches.

Justification: in this case, the quantity produced of product A may change but the quantity produced of product B is not significantly affected. Both subdivision and physical allocation approaches model the effects on environmental burdens of a multifunctional process where the quantity produced of one product is changed while the quantity produced of other products remains the same.

In the second case, possible actions can have a significant effect on the production of both products, as the production volume of both products is decided by the demand for product A. If there is a demand for the function provided by Product B, the additional amount of product B is likely to replace another product fulfilling this function. As an example, consider an LCA of a diamond product. The residues from diamond mining (product B in **Fig. 3**) are fully used in road construction. An increased use of diamonds results in an increased quantity of residues being available for road construction. This means that other road construction materials can be replaced. If part of Product B goes to waste prior to the change in volume of the diamond production, the change is likely to affect the waste management of Product B.

Our methodological recommendation in the second case is to include all environmental burdens from the multifunctional process in the system investigated. In addition, it should include the unit processes (if any) that would be affected by a change in the production of Product B, including the possible change in waste management of Product B and in the production of competing products (product C in Fig. 3). The consequential LCI model should also include any significant differences in the environmental burdens of the use and waste management of product B, compared to the use and waste management of product C.

Justification: the object of the consequential LCI is to include what is affected by a change in the use of product A in the life cycle under study. The multifunctional process is affected, since, in this case, it depends on the demand for product A. Hence, the multifunctional process should be included in the system. The production of product C could also be affected, as discussed above. If so, it should be included in the system investigated. The same applies to any significant differences in the use and waste management phases of other life cycles that result from the change from product C to product B.

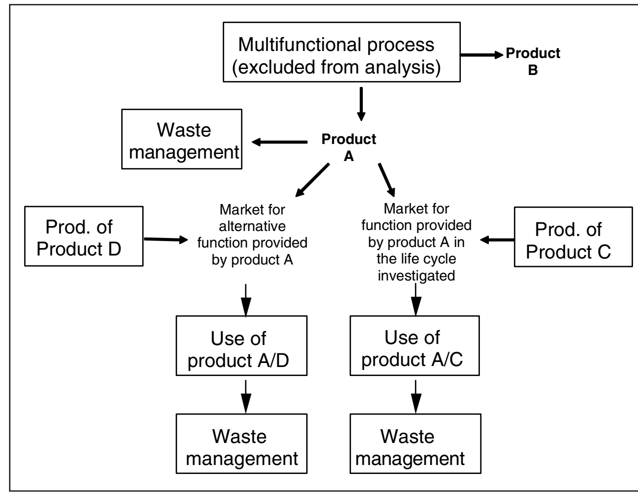

Fig. 4: Illustration of a theoretical multifunctional process and of the activities that may be indirectly affected by a change in the demand for Product A in the system investigated

The third case is when possible actions have little effect on the production of both products, because the production volume of both products is determined by the demand for product B. In this case, an increased use of product A in the system investigated will not affect the multifunctional process. Instead, one of three scenarios occurs. The first possibility is that the increased use of product A in the life cycle investigated results in a corresponding increase in the production of other products (product C in **Fig. 4**) that fulfil the same function as product A. If product A has more than one potential use, another scenario is possible: the result of an increased use of product A in the life cycle investigated is that a smaller quantity of product A is available for other purposes. This, in turn, could result in a corresponding increase in the production of other products that fulfil this alternative purpose (product D in Fig. 4). As an example, consider a hypothetical LCA of a table produced from particleboard that is manufactured from sawdust from a sawmill. The sawdust (product A) contributes little to the total revenues of the sawmill. The sawdust that is not used for particleboard production is sold at a lower price as for fuel. It is reasonable to assume that the sawmill processes are not affected by the demand from the particleboard producer. Instead, the effect of an increased production of particleboard is likely to be that less sawdust is sold as fuel and that other fuels (product D) will be used instead.

A third scenario is likely if part of product A goes to waste prior to the action: the increased use of product A in the life cycle investigated means that less goes to waste. As an example, consider an LCA of a road. Part of the residues (now product A in Fig. 1 and Fig. 4) from a mining operation is used in the construction of this road. The remainder of the residues are deposited in a landfill. The use of the residues in the road construction is unlikely to affect the mining operation. Instead, the effect of the decision to use these residues is that less residues end up in the landfill.

Our recommendation for the third case is to exclude the whole multifunctional process from the system under investigation. Instead, the system investigated should include any significant reduction in waste management or alternative uses of product A. Furthermore, the system should include the production of products C and D, if these are affected by the use of product A. The consequential LCI model should also include any significant differences in the environmental burdens of the use and waste management of product A, compared to the use and waste management of products C and D. In the particleboard example, the system investigated should exclude the sawmill, but include the avoided use of sawdust as fuel as well as the production and use of the fuel that is required to replace the sawdust. In the road construction example, the system should exclude the mining operation, but include the avoided landfilling of mining residues.

Justification: again, the object of the consequential LCI is to include what is affected by a change in the use of product A in the life cycle investigated. The multifunctional process is not affected, since, in this case, it only depends on the demand for product B. Hence, the multifunctional process should be excluded from the system. The production of product C and D might be affected, as discussed above. If so, they should be included in the system investigated. The same goes for the waste management of product A, if any.

Note that the three cases presented above are ideal, theoretical constructs. The behaviour of real multifunctional processes often is a combination of the different cases. Products from a multifunctional process can rarely be expected to be completely independent of each other (Ekvall & Finnveden 2001) and a multifunctional process can rarely be expected to depend on the revenues from only one of the products. The considerations above do not primarily refer to such total independence, but to the dependencies involved when the production and use of product A is slightly increased or reduced. For such marginal changes, the above considerations give a reasonable reflection of real dependencies. It should also be noted that the way in which products depend on each other in a specific production process could vary over time and from market to market.

The ideal option for dealing with the allocation problem caused by multifunctional processes is to include all unit processes to the extent that they are affected by a change in the use of product A in the life cycle investigated. A consequence of the previous paragraph is that this often means applying a combination of the approaches described above. Probably such a procedure is rarely feasible. Hence, simplifications are necessary.

One line of simplification is to apply only one of the above approaches for each multifunctional process. This requires that for each multifunctional process, one of the cases above is chosen as the best approximation of the behaviour of the real multifunctional process.

Another line of simplification is to use the easiest allocation approach for most of the multifunctional processes in the system investigated and only apply the more advanced approaches to the allocation problems that are expected to have the largest potential effect on the conclusions of the LCA. This requires that the potential significance of all allocation problems in the system be estimated in qualitative terms, based on, for example, previous experience or rough calculations.

There may be large uncertainties concerning what unit processes are affected, and to what extent, by the use of product A. When the uncertainties are large, and the effects may be significant for the conclusions of the LCA, it is reasonable for the study to include different scenarios based on various assumptions regarding the effects on the different unit processes.

3 Allocation for Open-Loop Recycling

As stated in the previous section, we describe allocation for open-loop recycling separately. Open-loop recycling is the recycling of material from one product system into another (ISO 1998). The allocation problem occurs when material is recycled from the system investigated as well as when material is recycled into it. The international standard for LCI allows for several different approaches to the allocation problem, although it states that the approach used for outflows of recycled material should be consistent with the approach used for inflows of recycled material (ISO 1998).

Quite often, if a material is recycled from the investigated system, it replaces other material, recycled or virgin in new products (**Fig. 5**). The effect of recycling material from old products into the system might be that landfill or waste incineration is reduced or that less recycled material is used in other product systems. In both cases, the ideal consequential LCI methodology is to expand the system under study to include the unit processes that are actually affected by an increase or reduction in the flow to/from the life cycle investigated. In this respect, open-loop recycling is similar to multifunctional processes, where the production of the external function depends on the demand for the internally used function (Case 2 in Section 2).

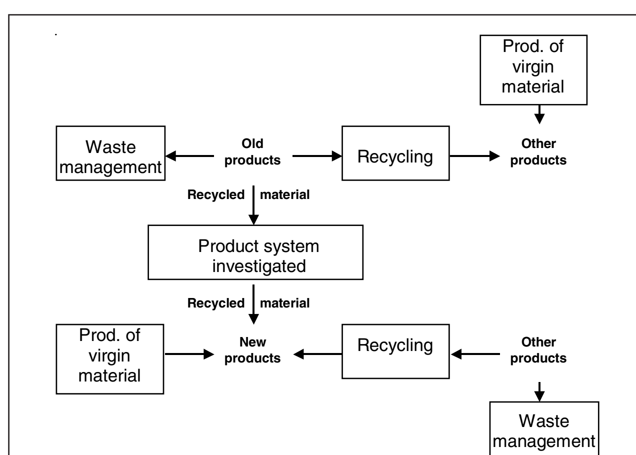

Fig. 5: Illustration of open-loop recycling to and from the product system investigated and of the activities that may be indirectly affected by a change in the quantities recycled

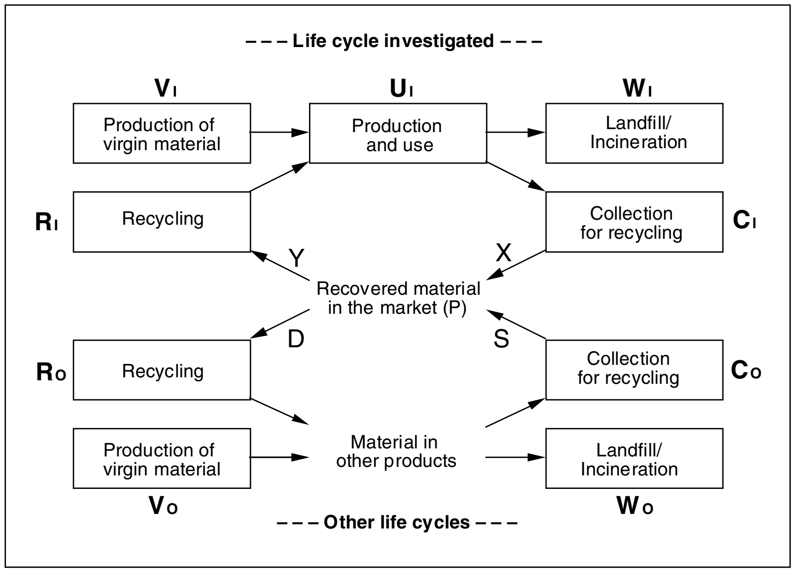

Fig. 6: A conceptual model of open-loop recycling through a market for recovered material (Ekvall 2000)

In practice, it can be difficult to identify what unit processes are actually affected by a change in the recycling flows. Recycled material from the system investigated can replace material of the same type, i.e. virgin material or recycled material from other systems. It can also replace completely different types of material or no material at all (Ekvall & Finnveden 2001). Recycling of material into the system investigated might affect different waste management processes. It might also affect several other systems, in which the recycled material could have been used, replacing another and unknown material. Again, simplifications are required to make the methodology operational.

A first line of simplifications is to assume that the recycled material only competes with virgin or recycled material of the same type. This assumption is, of course, valid unless the recycled material competes significantly with completely different types of material or with no material at all. With this simplification, we still need to establish to what extent recycled material from the system investigated replaces virgin material and to what extent it replaces recycled material from other systems. We also need to study to what extent the use of recycled material in our system results in reduced waste management and to what extent it results in a reduction in the use of recycled material in other systems. The static, conceptual model in **Fig. 6** can be used for this investigation. In this model, Y, X, D and S are flows of a specific type of recovered material to and from the market for that recovered material, and P is the price of the recovered material. The environmental inputs and outputs of different parts of the life cycle investigated are denoted $\mathbf{V_I}$, $\mathbf{R_I}$, $\mathbf{U_I}$, $\mathbf{W_I}$, and $\mathbf{C_I}$. The corresponding inputs and outputs from other life cycles are denoted $\mathbf{V_O}$, $\mathbf{R_O}$, $\mathbf{U_O}$, $\mathbf{W_O}$, and $\mathbf{C_O}$.
If the amount of recycled material from (or to) the product life cycle investigated is changed by ΔX (or ΔY), the effects on other life cycles can be calculated from the price elasticity of supply and demand in the market for recovered material. If X and Y are small compared to D and S, the price elasticity of supply (η_S) and demand (η_D) respectively is:

$$\eta_S = \frac{\Delta S/S}{\Delta P/P} \tag{1}$$

$$\eta_D = \frac{\Delta D/D}{\Delta P/P} \tag{2}$$

The effects, ΔD_X and ΔS_X, of a change ΔX can be calculated as follows (Ekvall 2000):

$$\Delta D_X \approx \frac{\Delta X \eta_D}{\eta_D - \eta_S} \tag{3}$$

$$\Delta S_X \approx \frac{\Delta X \eta_S}{\eta_D - \eta_S} \tag{4}$$

The effects, ΔD_Y and ΔS_Y, of a change ΔY can be similarly calculated:

$$\Delta D_Y \approx -\frac{\Delta Y \eta_D}{\eta_D - \eta_S} \tag{5}$$

$$\Delta S_Y \approx -\frac{\Delta Y \eta_S}{\eta_D - \eta_S} \tag{6}$$

In many LCAs X and Y can both be changed, and the total effects, ΔD and ΔS, are the sums of the equations above:

$$\Delta D \approx \frac{\eta_D}{\eta_D - \eta_S} (\Delta X - \Delta Y) \tag{7}$$

$$\Delta S \approx \frac{\eta_S}{\eta_D - \eta_S} (\Delta X - \Delta Y) \tag{8}$$

This elasticity approach requires that the relevant price elasticity values be identified. Values for price elasticity are generally identified through the use of time series and econometric models. The price elasticity strongly depends on the time horizon of the study. In general, the price elasticity is larger in a long-term perspective than in a short-term perspective since in the long-term perspective, decision makers are able to adapt to changes in the price when making investments. The price elasticity also depends on, e.g., the collection schemes and the legislation in place at that time and in that location. This means that the price elasticity should ideally be identified for each individual case of open-loop recycling. Unfortunately, this is not likely to be feasible. Instead, further simplifications are necessary.

For this second line of simplifications, several alternatives exist (**Fig. 7**):

- Use default values for the price elasticities, for example the values that are presented by Palmer et al. (1997) and summarized by Ekvall (2000); these values can be inserted as η_S and η_D in equations 7 and 8 above to calculate estimates of how the flow of the material to and from other life cycles are affected,
- Assume that the demand and supply are equally elastic ($-\eta_D = \eta_S$),
- Assume that the demand or the supply is completely inelastic (η_D or η_S is zero), or
- Develop multiple scenarios based on different choices among the above approaches.

The default values for price elasticity were applied by Berlin (2002) in order to model the consequences of cardboard recycling in an LCA of cheese. These were small compared to the total LCA results, which means that a simplified approach was fully justified. The main danger in using default values in other cases lies in a sense of false security. The actual elasticity in a particular recycling case can differ a great deal from the default values. For the price elasticity for the supply of old newsprint, the literature includes estimates ranging from 0.06 to 1.70 (Palmer et al. 1997). The extremely large span between the estimates may be due to errors in individual estimates, but it is also caused to some extent by case specific

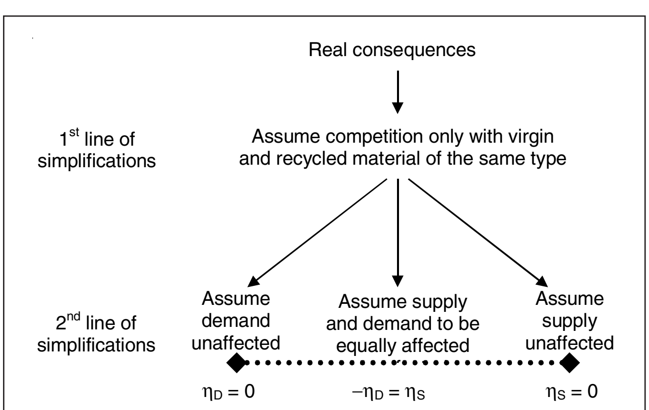

Fig. 7: Example of possible simplifications at consequential modeling of open-loop recycling. Additional alternatives for the second line of simplifications is to use default values for the price elasticities or to develop multiple scenarios based on different values for the price elasticities

factors such as the time horizon of the study and the time and place where the material was collected for recycling.

As an alternative to using default values, it can be assumed that supply and demand are equally elastic. The consequence of such an assumption is that 50% of the recovered material from the life cycle investigated in the LCI model replaces material recovered from other life cycles and the remaining 50% is a net increase in total recycling. With this alternative approach, the LCI model takes into account the fact that recycled material from the system investigated can replace virgin and recycled material from other systems. This approach was used for modelling the effect of PET recycling in a study on beverage packaging (Ekvall et al. 1998).

The third option is to decide whether the supply or the demand is the most inelastic, and set this elasticity to zero. In an LCI model based on this approach, recovered material from the system investigated only replaces virgin material or only material recovered from other systems. This approach might be easier to apply than the approaches above, because it renders the LCI model less complicated. Ekvall et al. (1998) used this approach to model the consequences of glass, steel and aluminium recycling. This simplification will probably not significantly affect the LCI results if the difference between the actual price elasticity of supply and demand is large for the recovered material.

There is apparently a large uncertainty in the price elasticity of supply and demand. When this uncertainty appears significant for the conclusions of the LCA, it is reasonable to develop different scenarios based on various assumptions related to price elasticity.

In many cases, open-loop recycling has a negligible effect on the LCI results. This is likely to be the case when, for example, the flows of recycled material are small compared to the flows of similar materials within the life cycle investigated. When there are good reasons, based on experience etc., to assume that the recycling has no influence on the conclusions of the LCA, the effects on activities outside the life cycle can be excluded from the study. A final line of simplification is to apply this simple cut-off approach to most of the flows of recycled material and apply the more advanced approaches to only the most important flows.

4 Alternative Use of Constrained Production Factors

A constrained production factor is here defined as a resource over which there is competition and where the production volume is constrained. Such resources include renewable as well as non-renewable resources. They include natural resources but also man-made resources (i.e., products), where the quantity produced is constrained by, e.g., legislation or physical restrictions.

An increased use of constrained production factors in the life cycle investigated does not affect the production or extraction of the resource. Instead, it means that less is available for other parts of the technological system. This, in turn, may result in an increased production of other products that fulfil the same purpose. A special case is a multifunctional process, where the production of the inherently used product depends on the

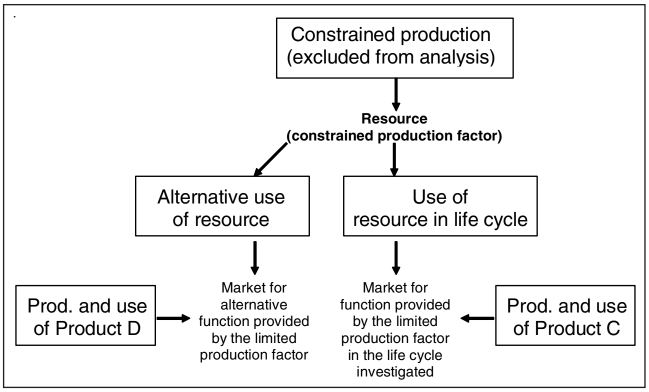

Fig. 8: Illustration of the production/extraction of a constrained production factor and of the activities that can be affected by a change in the use of this resource in the life cycle investigated

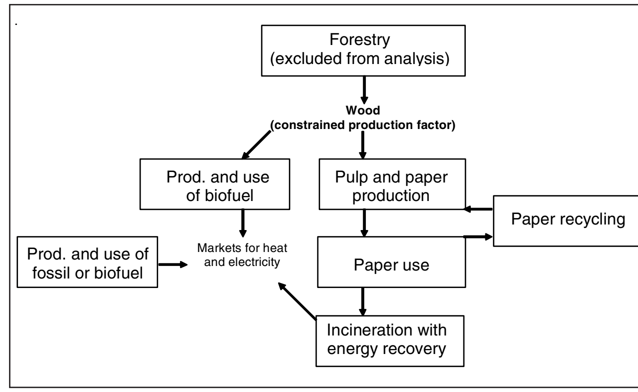

Fig. 9: Illustration of the analysis of alternative use of wood by Baumann et al. (1993)

demand for externally used products (Case 3 in Section 2). The ideal, consequential LCI methodology can be derived from this case, namely to exclude the production of the constrained production factors from the analysis, as long as it is unaffected by a change in the life cycle investigated. Instead, the system investigated should be expanded to include the alternative use of the constrained production factors and the production of the competing products (Product C and D in **Fig. 8**). The use and waste management in other life cycles should also be included if they are affected by a change from the constrained production factors to alternative products.

Note that the production of constrained production factors does not necessarily take place in multifunctional processes. In other words, this is a case where consequential LCI methodology calls for system expansion even though there may be no allocation problem.

As an example, consider the forest industry. Several LCAs have been performed in order to compare paper recycling with waste paper incineration and energy recovery (Finnveden & Ekvall 1997). In many cases the results indicate that the incineration option is preferable, because the energy from the paper may reduce the demand for fossil fuels. In simple terms, the overall effect of waste paper incineration may be that renewable energy in the form of pulpwood is transformed to paper and then used to replace fossil fuels.

It is not necessary to produce paper from the wood before it is used to replace fossil fuels. The recycling option results in a reduced demand for pulpwood. Since pulpwood is a renewable resource, this reduction in resource demand is often assumed to be of little or no environmental significance (Hauschild & Wenzel 1998, Steen 1999). However, in a sustainable future, forest areas and wood are likely to be a renewable but constrained production factor because arable land area will be required to produce food and energy as well as material. A reduced demand for pulpwood means, from a sustainable perspective, that more land will be available for energy production. Hence, in a sustainable future, the effect of saving pulpwood could mean the production of more renewable fuel with less impact on biological diversity etc. The alternative use of woodland as a source for energy has been included in a case study made to compare recycling and incineration of newsprint and corrugated board (Baumann et al. 1993; see **Fig. 9**). The alternative use of wood was shown to be a key issue in this comparison (Ekvall 1999b).

As a second example, consider hydropower. On some electricity markets, it is possible to buy electricity generated by a particular production technology. It may be possible to purchase, e.g., wind power or hydropower. When an electricity contract specifies the production technology, the electricity supplier is responsible for supplying the corresponding amount of electricity from this production technology to the grid. Kåberger & Karlsson (1998) argue that, in this case, data from the specified technology should be used in the LCA rather than average or marginal data for the geographical area. As an example, if the electricity contract of a Nordic aluminium producer specifies hydropower, data on hydropower production should be used in the LCA, rather than data on average or marginal electricity production in the Nordic countries. However, hydropower is a constrained production factor in the Nordic countries. An increase in the use of hydropower for aluminium production is not likely to result in an increase in total hydropower production in these countries. Instead, less hydropower will be available for other processes. If the electricity consumption of other consumers is unaffected, this means that the demand for the marginal electricity production technology is increased. Ekvall et al. (1998) argue that the long-term marginal technology for electricity production in the Nordic countries may be new plants based on coal or natural gas, or existing Swedish nuclear power. The alternative use of hydropower is obviously likely to be significant for the LCA results for an aluminium product. The identification of marginal technologies is further discussed in Section 7.

The examples above are not exhaustive. Oil and coal with low sulphur content is a constrained production factor. If a low-sulphur fuel is used in the life cycle investigated, fuels with higher sulphur content are likely to be used in other systems. Sawdust was previously regarded as a waste flow. Now it can be considered as a constrained production factor: if not used for the production of particleboard, it can be used for fuel production (see Section 2). There are probably many other such examples.

It is clear from the above that the alternative use of constrained production factors can have important, indirect effects. If these effects are included in the LCA, they may significantly alter the conclusions of the study. If they are not included, the conclusions may result in an environmental suboptimisation of the system, e.g., incineration with energy recovery of waste paper instead of recycling of paper combined with fuel production in the forest.

5 General Market Effects

A traditional LCA is based on the implicit assumption that an increased use of a product in the life cycle investigated will result in a corresponding increase in the production of that product. The discussion above illustrates that this is neither the case for certain products from multifunctional processes (Section 2, Case 3) nor for products for which the quantity produced is constrained by, e.g., legislation or physical restrictions (Section 4).

In fact, it is reasonable to expect that the assumption is invalid for products in general. Referring to the example of the particleboard table in Section 2, it is not certain that the production of particleboard is affected by decisions to purchase the table. The production of the table may even be unaffected. Instead, the effect of decisions to buy the table might be that less particleboard or fewer tables of this type are available for other purchasers. The indirect effects of buying the table may be that particleboard is replaced by other materials in other products and/or that the production and distribution of other types of tables are increased. This indicates that economic analyses of the table market, the table manufacturer, the markets for particle board and competing materials, the producer of the particle board and so on are required to accurately estimate the environmental consequences of buying the table.

This conclusion can easily be generalized for other products. Increased use of a product in the life cycle investigated is likely to contribute to an increase in the price of the product. This, in turn, is likely to result in a *reduced* use of the product in other life cycles. This can be called a negative feedback mechanism. The strength of the negative feedback and, hence, the effects of a change depend on how sensitive production and demand are to changes in price. This sensitivity can be quantified in terms of price elasticity (cf. Section 3).

On the other hand, the use of a new product in the life cycle may help the producer to establish the product on the market. It may also inspire others to use the product. These are positive feedback mechanisms: as a result of these mechanisms the increased use of a product in the life cycle investigated can result in *increased* use of the product in other life cycles.

Co-operation between economists and engineers is probably required to model the general market effects. Since price elasticity values etc. can be difficult to obtain, simplifications are also required to make the consequential LCI methodology applicable (cf. Section 3). The most obvious simplification is to reduce the size of the system investigated: to restrict the study to the activities that are expected to be most affected by the environmental impacts of the action, regardless of whether these activities are located within or outside the life cycle of the product investigated.

6 Identification of the Competing Product

Product substitution means that a product – including materials and services – is replaced by another. As indicated above (Sections 2 through 5), it is essential to know what products are likely to be substituted by, for example the coproducts or recycled material that leaves the life cycle when allocation is avoided by means of system extension. The following procedure (based on Weidema et al. 1999b) can assist in the identification of competing products:

The first step in this procedure is to describe the externally used product (e.g., product B in Fig. 3) in terms of its properties. These properties may be divided into three groups depending on their importance to the customer. Obligatory properties, which a competing product must have in order to be considered as an alternative, include the main function of the product. They can also include, for example, additional services, aesthetic properties, image, technical quality, reasonable total cost, and specific environmental properties. In addition, the product may have positioning properties, i.e. properties that improve the market position of the product when compared to products with similar obligatory properties.

The second step of the procedure is the identification of the market segments that are affected by the externally used product. Different market segments can be geographically separated, due to climate, regulations, consumer culture, etc. Within a certain geographical area, similar products with slight differences in the obligatory properties may serve different needs and, hence, affect different customer segments. Weidema et al. (1999b) also mention market segmentation in terms of the temporal aspects of the products. This includes peak time electricity and rush hour telecommunications.

The third, and final, step is to identify the competing products in the market segment affected. These are products with the same obligatory properties as the externally used product. Several competing products may of course exist in each market segment. The LCI model should ideally include all competing products that are significantly affected by a change in the production of the externally used product. The elasticity approach in Section 3 describes how the affected products can be included in the case of open-loop recycling. Section 7 includes a more general description of how to identify the production technologies that are affected by a marginal change in the demand or supply in the market segment.

The performance of a detailed analysis of all product substitutions in the expanded LCI model, as outlined in this section, is unlikely to be feasible. The most obvious line of simplifications is to restrict the detailed analysis to the product substitutions that are expected to be the most important to the conclusions of the LCA.

7 Identification of the Marginal Technology

A specific product might be produced by means of different technologies. Electricity, for example, can be produced with technologies with quite diverse environmental properties. As stated above, a consequential LCI aims at describing the consequences of changes. This means that the input data used for modelling the production of a specific product should reflect the relevant properties of the technologies that would be affected by a change in the life cycle investigated. If the effect of a decision on the total production volume of a product is small enough to be approximated as infinitesimal, it is termed a marginal effect. The technology affected by such marginal changes is called marginal technology.

The procedure presented below can assist in identifying marginal technologies. It is based on a five-step (a-e) procedure presented by Weidema et al. (1999) and essentially aims at answering two questions:

1. What is the situation in which the studied change in demand occurs? The first three steps (a–c) deal with this question.
2. Given this situation, what specific technology is affected by the change? The last two steps (d–e) aim at identifying this technology.

a) What are the relevant time aspects?
Economists distinguish between short-term and long-term effects of a change. Short-term effects only include effects on the utilization of existing production capacity. The capacity itself is assumed to be constant in the short-term perspective. When long-term effects are investigated, the production capacity is assumed to adapt to the change, and the utilization of this capacity is assumed to be constant.

In reality, any change can be expected to have a combination of short-term and long-term effects. In addition, short-term as well as long-term effects can be fairly complex in a dynamic system. For example, the short-term effects of an increased electricity demand are likely to concern technologies for production of a mixture of peak-hour and base-load electricity. The long-term effects can include consequences for investments in various technologies (Mattsson et al. 2001). Hence, the actual marginal effects can be too complex to model accurately.

In this case an obvious line of simplification is to adapt the distinction made by economists between a short-term and a long-term perspective and to include in the model either the short-term or the long-term marginal effects. What effects should be included depends on the time perspective of the study as a whole but, in most cases, we expect that the long-term effects will be the most relevant to the model, because environmental studies are typically driven by a concern for the long-term situation, and because individual short-term decisions contribute to the accumulated trend in the market volume, which is the basis for decisions on capital investment (i.e. long term effects).

A second line of simplifications is to ignore the dynamics of the system. This means that the system is modelled as a static system before and after the implementation of any changes in the life cycle investigated.

b) Are specific processes or overall markets affected?
If a decision will only affect a specific process, then the technology of this process is per definition the marginal technology. If the decision influences a market, it is necessary to identify the marginal technology of this market. The identification of the relevant market segment is described in Section 6. The subsequent steps (c–e) describe the identification of the marginal technology in this market.

c) What is the trend in the market?
If a market is affected, the next step is to identify the overall trend in the demand on the relevant market segment. This is often given by statistical time series. The trend need not be precisely described. It is sufficient to determine whether or not the overall demand on the relevant market segment is decreasing at a rate that is higher than the replacement rate of existing production capacity. If so, the long-term marginal technology is the technology that is most likely to be phased out. If the demand is increasing or decreasing at a slower rate, the long-term marginal technology is likely to be the technology chosen when new production capacity is installed.

d) What technologies are flexible?
If the production capacity – or the rate of change in terms of capacity – of a technology is fixed, its capacity cannot be affected by any decisions based on the LCA results. Hence, it can never be the long-term marginal technology. If the production volume – or the rate of change in production (cf. Section 4, and case 3 in Section 2) – is fixed, it cannot even be the short-term marginal technology. There may be many reasons for a technology to be constrained in its ability to adjust its production capacity or its production volume:

- natural constraints: e.g., the amount of water available in a specific region (cf. Section 4),
- political constraints: e.g., emission limits, quotas, ban on specific technologies (cf. Section 4), and
- market constraints for co-products: e.g., co-generated heat, animal products (cf. case 3 in Section 2).

In some cases, these constraints can be affected by changes in the life cycle investigated. For example, a change in the electricity demand may influence the political constraints on nuclear power in Sweden and Germany (Ekvall et al. 1998) or on coal power in Denmark. Ideally, the effects of changes on these constraints should be taken into account in a consequential LCA. In reality, such effects are probably too difficult to model. Hence, an obvious line of simplification is to treat the constraints as fixed entities when the model is developed. This means that any effects on the constraints are disregarded.

e) What technology is actually affected?
The marginal technology is among the technologies where the production or the production capacity can be adjusted in response to changes in the life cycle investigated. Long-term effects will take place either in the technology that is most likely to be phased out or the technology that is most likely to be installed (see above). These preferences are typically determined by the production cost per unit. The technology to be phased out is likely to be the installed technology with the highest short-term costs. The technology to be installed is likely to be the technology with the lowest long-term costs.

In some cases, several technologies can compete at the same cost. In this case, the marginal effects are likely to concern a mix of technologies, even when the model includes only short-term or long-term marginal effects and the dynamics of the system are disregarded. The most accurate LCI model is obtained if each affected technology is included in the LCI model in proportion to the price elasticity of supply for this technology. A simplified method is to include in the model only the technology that appears to be the most sensitive to changes in demand on the market.

8 Technology Development

Decisions that are affected by the consequential LCI, and the consequences of these decisions, take place after the study has been completed. Describing such consequences requires an investigation into the future. It is a historic fact that many technologies have been significantly refined over the years. As a consequence, the energy demand and emissions per functional unit have often been radically reduced. This indicates that it is not reasonable to assume that the environmental properties of the technologies in a future system are accurately described through the use of data that represent current technologies.

At the same time, it can be hazardous to take future technological advances into account in an environmental assessment of future systems. The type and magnitude of future environmental improvements are uncertain. The uncertainty can be dealt with through the development of different scenarios based on various assumptions regarding technological development. This reduces the risk that future environmental improvements are taken for granted. Several possible tools for such scenario development are available (Weidema 2003). The different tools can be used for generating various types of knowledge about the future. Extrapolation and dynamic modeling often aim at describing the expected, surprise-free, or most probable future. Exploratory methods aim at describing the variation of possible futures. Normative methods aim at describing routes to a desired future. Consequential LCI typically aims at foreseeing consequences. This indicates that extrapolation and dynamic modeling can often be relevant tools for describing technology development in a consequential LCI. However, exploratory methods can be used for generating scenarios that illustrate the large uncertainty in the technological development.

9 General Discussion and Conclusions

The distinction between a consequential and an attributional LCA was developed in the process of resolving the methodological debates over allocation problems and the choice of data. However, it is clear from this presentation that the aim of describing the effects of decisions on environmentally relevant physical flows has consequences beyond the problems of allocation (see Sections 2 and 3) and marginal data (Section 7). The parts of the technological system in such a description include the alternative use of constrained production factors (see Section 4). They also include the marginal supply and demand on markets that are affected by decisions in the life cycle investigated (Sections 5 and 6).

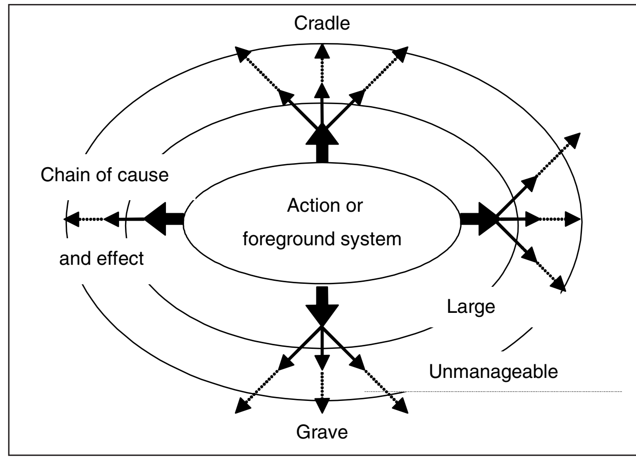

Fig. 10: The consequences of changes made by a decision-maker propagate through the overall economic and technological systems and not only upstream and downstream in the life cycle (Ekvall 2003)

When the aim is to describe the consequences of changes, it is usually not sufficient, and perhaps not even relevant, to trace the materials in the product investigated back to the cradle – that is, to the extraction or generation of the natural resources. The decision to buy the product does not necessarily imply an increase in the amount of natural resources extracted. In general terms, the consequences of an action do not necessarily propagate through the life cycle, but through the overall economic and technological systems in chains of cause-and-effect relationships, somewhat resembling the ripples caused by a stone thrown in a lake (**Fig. 10**).

The natural starting point of a consequential LCI of a specific decision is the decision itself – that is, the point where the stone hits the water. The consequential LCI describes how the decision affects the technological activity, both directly where the decision is implemented and its secondary effects on the use of intermediate products. It goes on to describe how this decision is expected to affect, for example, the production of these intermediate products as well as the use of the intermediate products in other processes. If it is possible to go further, the consequential LCI describes how these changes, in turn, are expected to affect other production processes, the use of energy, material and products in other parts of the technological system, and the environmentally relevant physical flows to and from the affected activities. Hence, the consequential LCI model does not resemble the traditional LCI model, where the main material flows are described from raw material extraction to waste management. Instead, it is a model of chains of causal relationships.

In this context economic causal relationships are at least as important as physical flows. The effects of a decision depend on how sensitive the production and demand of affected products are to changes in the price (see Section 5). They also depend on how easily the affected product can be substituted for other products and on the likely substitute products (Section 6). Such aspects are included in economic partial equilibrium models (Bouman et al. 2000). Hence, a solution might be to integrate partial equilibrium models into the LCI. Bouman et al. state that different types of models generate different and complementary types of information. They suggest that an integration of different tools entails a risk that the specific advantages of the different tools are lost. However, in this case, the integration of tools – LCI and partial equilibrium analysis – would result in a new tool with specific advantages with regard to modelling the consequences of changes.

It is reasonable to expect that the uncertainties in the economic analysis will be significant. Describing the consequences of decisions also means facing the general challenge of futures studies. The future is inherently uncertain, and the actual future consequences of decisions are highly uncertain. Dealing with this uncertainty requires that methods of futures studies are applied in the consequential LCI. The large uncertainties also make it impossible or pointless to estimate the consequences far down the cause-and-effect chains. This implies that the boundaries of the system investigated should ideally be defined at the point where the consequences are so small, or the uncertainties so large, that further expansion of the boundaries will yield no information that is significant for any realistic decision.

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