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"Guidelines for applications of deepened and broadened LCA"

Consequential LCA

1. Introduction
This chapter presents the topic of consequential LCA, with a focus on guidelines for current best practice and identification of gaps for future research. It has been primarily written by Bo Weidema from 2.-0 LCA consultants with Tomas Ekvall (IVL) as a co-author from the CALCAS project.

The chapter is structured as follows. First, we define and describe the different elements. Next, in section 3 we discuss the application areas relative to attributional modelling. The main part of the chapter is the guidelines in section 4. We end with a discussion of present limitations in section 5 and some research proposals in section 6.

2. Definitions and short description
In the context of LCA, the term *consequential* describes a modelling approach that seeks to describe the consequences of a decision. The term was first used on a workshop in 2001 (Curran et al. 2002), inspired by the suggestions of Frischknecht (1998) and Tillman (1998) that two very distinct perspectives of LCA exist: What Tillman calls LCAs of the *accountancy* type, by later authors named status-quo or descriptive LCAs and now known as *attributional*, as opposed to the *effect-oriented* or change-oriented LCAs, now known as consequential. Ekvall et al. (2005) link the approach to consequential (teleological) ethics, as opposed to deontological or virtue ethics.

It can be argued that all LCAs ultimately aim at supporting decisions on the substitution between two product systems (Weidema 2003). In one way or the other, studies of a single product are always later used in a comparative context. Even for hot-spot-identification and product declarations, what appears to be stand-alone assessments of single products have the ultimate goal to improve the studied systems, thus supporting decisions that involve comparisons:

- If a hot-spot-identification of a current product identifies a number of improvement options, it is still necessary to assess the environmental impact of implementing the improvements, namely the difference in impact between the improved and the current product, obtained as a result of adding the improved product and removing the current product.
- Product declarations are used by the customer to make a choice between several products, and the (intended) effect of this choice is that more of the chosen product will be produced at the expense of the competing products. Thus, the impact of the choice is obtained as a result of adding one unit of the chosen product and removing the corresponding amount of the current average product.

Consequential modelling can be applied both to LCI and LCIA. Most current LCIA models are consequential in the sense that they model the consequences of one additional unit of a specific emission, rather than the average consequences of all emissions. The below text is limited to the treatment of consequential modelling in LCI.

Consequential LCI modelling can be defined as a linking of unit processes in a product system so that unit processes 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 product. Change is here not meant in a temporal sense, as a change modelled over time, but simply as a comparison of the situation with and without a specific demand, that is, a change in the initial assumptions. Consequential models are steady-state, linear, homogeneous models, with each unit process fixed at a specific point in time. However, external dynamic models may be applied to generate input data. The modelling may be either marginal (for small changes) or incremental (for larger changes). The following guideline describes how to construct a linear model that is different depending on the size of the change studied. Thus, within each model, the answer is the same independently of the size of the change, but the choice of specific model is determined by the size of the studied change.

3. Application areas

As indicated above, consequential assessment, and therefore also consequential modelling, is relevant in most application areas of LCA. However, there are application areas where consequential modelling is less relevant, and an attributional model could be considered. Examples of such application areas are:

- Studies at a societal level, where the entire environmental impact of all human activities is studied, with the aim of identifying areas for improvement, disregarding whether such improvements shall be sought through product-oriented policies or through direct regulation of the individual activities. In such a situation, it would not be reasonable to limit the study to those activities that can be affected by changes in demands, but to include all activities, also those that are not linked to any consequential product system, and for which a policy-driven improvement can only be achieved through direct regulation. One can argue that since the objective of such a study is not product-oriented, LCA is simply not the (only) relevant assessment technique. An attributional model, where all activities in society are included in proportion to a specific attributional rule, such as revenue, would better reflect the objective of such a study. Once improvement options are identified by such a model, those improvement options that have upstream or downstream consequences can then afterwards be studied with a consequential model. The IMPRO study on meat and dairy products (Weidema et al. 2008) is an example of such an attributional study at the level of EU-27, where the identified improvement options were analysed with a consequential model.
- Studies on environmental taxation, where the focus is less on the consequences of the tax, but rather on who is to carry the burden. Often, studies on taxes or quota systems are performed for a specific administrative area, and any consequences outside this administrative area are discounted. Although the consequences of a tax on a product or an activity can be studied by a consequential model, this model cannot say anything about the attribution of the tax and its fairness. An attributional model, where all activities in society are included in proportion to their perceived contribution to the taxed activity variable, whether or not this changes as a consequence of the tax, would better reflect the objective of such a study.
- Studies that seek to avoid blame or to praise or reward for past good behaviour, for example avoiding blame that a specific deplorable activity, such as slavery, occurs in the product system, or rewarding producers that have invested in a praiseworthy technology such as wind-power. While a consequential model can answer the question whether the deplorable or praiseworthy activity *changes* as a consequence of buying the product, it cannot tell how much of the deplorable or praiseworthy activity *exist* in the product system, simply because a consequential product system does not *exist*, it

happens. An attributional model, where activities are included in proportion to a specific attributional rule, for example mass, energy or revenue, would better reflect the objectives of such studies.

The focus of the following guideline on consequential LCI modelling is the identification of the unit processes that change as a consequence of a decision, when these processes are linked via a market. As such, the procedures in the guideline are *not relevant* if the affected unit processes are already known, that is, if only one supplier exists, or if a specific group of enterprises are so closely linked in a supply chain that the production volumes of the specific suppliers can be shown to fluctuate with the demand of the specific customers. Examples of the latter situation can occur when:

- Products have a low price compared to their weight, so that transport costs prohibit all other than the local producers, as for example for the supply of straw for heat and power production, where only the farmers closest to the power plant will supply the straw. Other examples of this can be found in the forestry sector and the building- and glass-industries.
- Two or more companies are tied together by tradition, or when a supplier has developed its product to meet specific demands of the customer.
- The choice of supplier is not subject to normal market conditions.

> As a default, when there is no information available to justify that a specific supplier (or group of suppliers) will be the one affected, it is advisable to assume that a market will be affected, and that the below guideline therefore is applicable. This is the typical situation, and by applying this default the burden of the proof rests on the companies having established such close market ties, and that therefore have the best access to the information on these.

4. Guideline

Introduction

It follows from the definition of consequential LCI modelling provided above, that the key issue in consequential LCI modelling is the identification of the unit processes that change as a consequence of a decision. This key issue then has implicit consequences for three central elements of the LCA technique:

- How unit processes are linked into product systems via intermediate product flows, as identified via the expected reactions of suppliers and users
- How to deal with unit processes (or product systems) with multiple products.
- How the functional unit and reference flows should be defined.

In the following, each of these three elements will be described in turn, providing step-by-step procedures, based on Weidema (2003) slightly modified[1] and expanded. The first procedure is the central one, and the following two can be seen as logical consequences of the first.

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[1] The most important modifications are:

a) Market boundaries are now described consistently as identifiable by a negligible flow of products across the boundary, and the recommended default for market boundaries is now *no* boundaries unless justified, as opposed to more narrow boundaries in Weidema (2003). The new recommendation is more consistent with the rest of the modelling.

b) The procedure to include downstream consequences of differences in non-market properties has been generalised, while in Weidema (2003) it was presented only in relation to non-market properties of dependent co-products.

The first procedure, for identification of which unit processes to link, has four steps:

- Identifying the scale and time horizon of the potential change studied
- Identifying the limits of a market
- Identifying trends in the volume of a market
- Identifying changes in supply and demand

Identifying the scale and time horizon of the potential change studied

The scale and time horizon of a decision is relevant because it delimits what suppliers, markets, products and technologies can be affected by the decision.

The scale of the studied decision can be small (marginal) or large. A decision is defined as small or marginal when it does not affect the determining parameters of the overall market situation, that is, the direction of the trend in market volume and the constraints on and production costs of the involved products and technologies. The consequences of the decision can thus be assumed linearly related to the size of the change and both an increase and a decrease in production volume will affect the same processes. A decision is defined as large when it affects the overall market situation, and therefore may bring into play new suppliers, new markets, or even new products and technologies. The consequences can therefore not be assumed linearly related to the size of the change and increases and decreases in the production volume may affect different processes. For large decisions, it is therefore necessary to take the direction of change into account.

Large changes are typically seen when introducing new technology or new regulation on a significant market, for example if all cars were to be made from polymers and carbon-fibres in stead of steel, which among other consequences might have the market for steel turning from increasing to decreasing. However, many small changes may accumulate to bring about a large change. Therefore, even in studies of small changes it may sometimes be relevant to apply an additional scenario with the possible larger changes that could be the result of accumulated small changes. For example, even in an LCA considering a shift to polymers and carbon fibres for a single producer of cars, it may be relevant to investigate the possible consequences of other car producers following suit.

However, the typical decisions studied by LCA are (unfortunately) not of such significant size. As shown by Mattsson et al. (2001), even a change in the annual electricity demand by 1 TWh can still be regarded as small (marginal), since it affects the same technologies as a change of 1 kWh, which means that the effects are linearly related to the size of the change.

> As a default, when there is no information available to justify that the studied decision affects the determining parameters for the overall market situation, it is advisable to assume that the studied change is small, since this is the typical situation.

The time horizon of a decision is obviously of interest because the background conditions may change over time, requiring different (forecasted) models to be applied. This is particularly relevant when comparing large investments, where decisions may lock technological developments to a specific direction.

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c) The modelling of the consequences when a co-producing unit process has more than one determining product has been made more explicit, and now includes also the reduction in consumption.

The issue of time horizon also concerns the distinction between short-term and long-term changes. A short-term change affects only capacity utilisation, but not capacity itself. A long-term change affects also capital investment (installation of new machinery or phasing out of old machinery). Large changes will always affect capital investment. But even the effect of small, short-term changes can seldom be isolated to the short-term perspective, since each individual short-term purchase decision will contribute to the accumulated trend in the market volume, which is the basis for decisions on capital investment (long term changes). This is obvious in free market situations (where market signals play a major role when planning capacity adjustments) with a short capital cycle (fast turnover of capital equipment, as for example, in the electronics and polymer industries), but it is also true for markets with a long capital cycle (as for example, in the building and paper industries). Thus, pure short-term effects of small, short-term changes (effects within the existing production capacity, including reduction in current capacity) are only of interest in markets where no capital investment is planned (for example, industries in decline), or where the market situation has little influence on capacity adjustments (monopolised or highly regulated markets, which may also be characterised by surplus capacity). An example of a substitution with a short-term effect only would be an isolated decision to remove heavy metals from the components of a product, which – all other things equal – would not involve capital investment in the metal industry, since heavy metals are already being phased out.

If a long-term substitution is planned and announced well in advance of its implementation (as for example, the installation of a new pipeline), it may involve only long-term effects, namely the effects from installation and production on newly installed capacity. But such planned decisions are the exception. Most long-term product substitutions will also lead to some immediate short-term effects, affecting the existing capacity, while at the same time affecting investments decisions and in the long run affecting the production from this newly installed technology. Since the technology affected in the short term will often be old technology (the least competitive technology which typically has a low capacity utilisation compared to newly installed technology) while the technology affected in the long term will often be modern technology, long-term product substitutions may thus often be seen to affect a mix of technologies (Mattsson et al. 2001). However, the short-term effect will typically be negligible compared to the long-term effect, simply because the long-term effect is typically more permanent, while the short-term effect only lasts until the next capacity change.

Consider a factory in which several production lines exist, some using an older technology, which is more polluting and more expensive to run, and some with a new technology (less polluting, less costly to run). Small, short-term fluctuations in demand will affect the capacity utilisation of the production line with the older technology (since this is the most costly to run), while the line with the new technology will be utilised as much as possible, and will therefore not be affected. If the demand increases beyond what can be covered by the current capacity, new machinery will be installed, and here the factory may choose to install the newest technology even though it is more costly to acquire, or it may decide to buy a cheaper, but more polluting technology. Whatever the choice, this can be said to be the long-term result of the change in demand and the additional environmental exchanges from the factory are now those coming from the newly installed machinery. It is therefore these exchanges that it would be reasonable to ascribe to the change in demand. Once the new machinery has been installed, further changes in short-term demand will still affect the older technology (since this is still the most costly to run). It is important to understand that even though the short-term fluctuation constantly will affect the older technology in the short-term, it is the accumulated changes in the short-term demands that make up the long-term changes, which eventually lead to the installation of the new machinery. The long-term effect of the demand is therefore the additional exchanges from the newly installed technology, and the short-term effects can be seen as a mere background variation for this long-term effect. Thus, the long-term effect should also be guiding for decisions that at first sight appear short-term, such as individual purchase decisions, and the product declarations that support such decisions.

> As a default, when specific information is not available, it is advisable to assume that the effect of the studied change is long-term, since this reflects the typical and dominating effect.

Market delimitation
Markets link users and suppliers, and are therefore central in delimiting what users and suppliers can be affected by a specific decision.

Markets are typically differentiated
- geographically,
- temporally, and
- in customer segments.

The geographical segmentation of markets may be determined by differences in:
- natural geography (climate, landscape, transport distances etc.),
- regulation or administration (regulation of competition and market transparency, legislative product requirements, product standards, taxes, subsidies),
- consumer culture.

Geographical segments can be identified and documented by the lack of imports and exports of the product across the geographical boundary.

Temporal segmentation of markets is common for service products (for example, peak hours and night hours in electricity consumption, rush hours in traffic and telecommunication, seasons in the tourist industry). For physical goods, markets are generally only segmented temporally when adequate supply or storage capacity is missing, either due to the nature of the product (for example, food products), or due to immature or unstable markets, as has been seen for some recycled materials.

This temporal segmentation should be distinguished from the fact that *markets generally develop in time*, for example governed by developments in fashion and technology, and that both geographical and temporal segmentation and customer segmentation therefore may change over time. In general, there is a tendency for markets to become more transparent and geographically homogenous with time, but at the same time more segmented with regard to customer requirements and thus product differentiation.

Customer segmentation within each geographical market is defined in terms of clearly distinct function-based requirements. These are based on the needs fulfilled by the products rather than on the physical products themselves. Very similar products may serve different needs and hence serve different markets. And very different products may serve the same need, thus being in competition on the same market. This can be expressed in terms of the *obligatory properties* of the product, which are the properties that the product *must have* in order to be at all considered as a relevant alternative.

Product properties may be related to:

- Functionality, related to the main function of the product
- Technical quality, such as stability, durability, ease of maintenance
- Additional services rendered during use and disposal
- Aesthetics, such as appearance and design
- Image (of the product or the producer)
- Costs related to purchase, use and disposal
- Specific environmental properties

Functionality, aesthetics, and image characterise the primary services provided to the user. Technical quality and additional services ensure the primary services during the expected duration of these. Of the above-mentioned properties, price is the only one that can be put into well-defined terms. Technical quality and functionality can be described a little less well defined, but still quantitatively. Other properties, such as aesthetics and image, cannot be measured directly, but must be described qualitatively. Some of these properties can seem very irrational, since they are not present in the product, but in the buyer's perception of it. These properties can be greatly influenced by the marketing activities of the supplier. Differences in customer requirements may be based on differences in the purchase situation, the use situation, customer scale, age, sex, education, status, "culture", attitudes, etc.

To have a practical relevance, market segments must be of a size that can provide adequate revenue to support a separate product line, and *clearly distinct with a minimum of overlap*, so that all products targeted for a segment are considered substitutable by the customers of this segment, while there should be low probability that a product targeted for another segment would be substitutable, implying that product substitution from segment to segment can be neglected.

Market segments may be further sub-divided into market niches. A *market niche* is a sub-category of a market segment, where a part of the customers consider only niche products substitutable, although the majority of the customers allow substitution between products from the niche and other products in the segment. Thus, the difference between a segment and a niche is that between segments substitution is negligible, while a large part of the customers in a segment will allow substitution between niche products. Niche products are aimed at a smaller group of consumers within a segment, for whom specific product properties are obligatory, while the same properties in the broader market segment are only *positioning properties*, which are the properties that are considered *nice to have* by the customer and which may therefore position the product more favourably with the customer, relative to other products with the same obligatory properties.

> As a default, if no information is available to justify a market boundary, it is advisable to assume that no market boundary exists, since this is the most general situation.

It may be useful to model markets explicitly as part of the LCI by introducing unit processes representing market activities in-between the using and supplying activities. Such market activities, having the same product in as out, can be used to document the assumptions on market delimitations, to add trade and transport activities and their associated costs, to model product losses during trade and transport, to add data on product taxes or subsidies, and to document the specific balance of supply and demand (see below).

Although different products traded in the same market segment or niche by definition have the same obligatory product properties, they may very well be different with respect to *non-market* properties, the properties that do not play a role for the customer's preferences. For example, while all beverage containers must fulfil the obligatory product property of non-leakage, different (refillable) beverage containers in the same market segment may differ in terms of ease of cleaning before refilling. Such non-market product properties may still give rise to consequences that should be included in the product system. For example, the beverage container that is easier to clean may affect the type and amount of cleaning agent used. This can be done *either* by modelling the downstream activities explicitly for the product in question, rather than for the average, *or* by moving the difference in the downstream activities relative to the averages from the downstream activities to instead be an input to the producing process, in parallel to the way downstream waste treatment and recycling activities are modelled as inputs of waste treatment services, rather than as downstream activities. The latter alternative is the only way this can be implemented consistently in a larger LCI database.

Trend in volume of the affected market

The market trend ("Is the market increasing or decreasing?") is important to know, because changes will affect the market differently, depending on whether the market is increasing or decreasing, especially when we consider long-term changes involving capacity adjustments. If the market is generally increasing, stable or slowly decreasing (at a rate *less* than the average replacement rate for the capital equipment), new capacity must be installed, typically involving a modern, competitive technology, and any change will affect the decision on this capacity adjustment. In a market that decreases rapidly (at a higher pace than what can be covered by the decrease from regular, planned phasing out of capital equipment) the affected suppliers will typically be the least competitive (often using an older technology).

It follows from the above distinction, that if the general market volume is decreasing at about the average replacement rate for the capital equipment, the effect of a change may shift back and forth between suppliers with very different technologies, which makes it necessary to make two separate scenarios. This may be relevant for a fairly large interval of trends in market volume, since the replacement rate for capital equipment is a relatively flexible parameter (planned decommissioning may be postponed for some time, for example by increasing maintenance). In general, the replacement rate for production equipment is determined as the inverse of the estimated lifetime of the equipment.

Note that it is the overall market trend, which is of interest, and not the direction of the change in demand implied by the specific decision studied. This is because – as long as the overall trend in the market is not affected – the same suppliers will be affected by an increase and a decrease in demand resulting from individual decisions.

Market trends are typically obtained by combining statistical data showing the past and current development of the market and different forecasts and scenarios. Sector forecasts are typically available from national and supranational authorities, while more product specific forecasts are available from industrial organisations.

> As a default, when information on market trends is not available, it is advisable to assume an increasing or stable market, since this is – in spite of obvious exceptions – the general situation for most products, due to the general increase in population and wealth.

Changes in supply and demand

In LCA and IOA, it is normal practice to assume full elasticity of supply. This means that if the demand increases with one unit, the producers will react by increasing their supply with one unit, and conversely when the demand decreases. This makes it straightforward to trace the changes in the product system upstream, simply by following the increases in outputs of the upstream activities required to satisfy the increases in demand of the downstream activities.

The assumption of full elasticity of supply is in accordance with the theoretically expected long-term result of a change in demand on a unconstrained, competitive market, where there are no market imperfections and no absolute shortages or obligations with respect to supply of production factors, so that production factors are fully elastic in the long term, and individual suppliers are price-takers (which means that they cannot influence the market price) so that the long-term market prices are determined by the long-term marginal production costs (implying that long-term market prices, as opposed to short-term prices, are *not* affected by demand).

When suppliers are constrained or markets are imperfect (so that producers can influence the market prices), the assumption of full elasticity of supply should be modified. There can be many different types of constraints to consider, notably regulatory or political constraints, and constraints in the availability of raw materials, waste treatment capacity, or other production factors.

The ultimate market imperfection is when there is only one supplier of the specific product (a monopoly). However, such situations are becoming more seldom as even the so-called natural monopolies, such as the railroads, telephone and electricity markets, which were long divided into regional monopolies, are now being opened up to competition. Still, patents and product standards may limit market entry of new suppliers, and transaction costs may be prohibitive for some potential suppliers to be involved in practise.

Regulatory constraints typically take the form of minimum or maximum quotas on the activity or any of its exchanges, for example product quotas or emission quotas. The regulatory forced phasing out or in of specific technologies may also render these unavailable to respond to changes in demand. Taxes and subsidies may also constitute virtual constraints on production.

For multi-product processes, supply of a co-product may be constrained if it does not have a value that can sustain the production alone. In general, this will be the case if the co-production is the only production route available for one of the other co-products, or if the market trend for the studied co-product is low compared to the market trend for the other co-products.

The necessary production factors may not be locally available or may only be available in limited quantity (for example, the availability of fresh, untreated drinking water may be limited in areas with limited rainfall, water for hydropower likewise, and on an expanding market for a material, the availability of recycled material will be constrained). For inputs that do not store easily and inputs with a low price to weight ratio (such as gravel), transport distances and infrastructure can impose a constraint on products and materials not produced locally. Waste treatment capacity may be a constraint on processes with specific hazardous wastes.

If all suppliers to a specific market segment are constrained, or if one or more production factors are not fully elastic (for example due to reduced resource quality or increased transport requirements to increase availability), a change in demand will lead to a change in market price and a consequent adjustment in demand. This adjustment will be accommodated by the customer(s)/application(s) most sensitive to changes in price, as determined by their demand elasticity (their relative change in demand in response to a change in price). This change must then be followed forward (downstream) in this lifecycle.

In equilibrium analysis, the assumptions of full supply elasticity and absolute constraints are relaxed, and it is attempted to find more empirically based elasticities, especially for the main factors of production, imports and exports, and for the consumer demand. However, empirical studies are seldom applied to the supply and demand elasticities of substitutable products/technologies relevant for LCA modelling. A fundamental problem of empirically based elasticities is that they are typically short-term elasticities, since these are the elasticities that are easily measurable in practice. Thus, if we want to model long-term changes involving investment decisions, we rather need models of investment decision making, for which long-term production costs appear better determinants than short-term market behaviour.

As with any other market condition, production constraints may change over time, depending on location, and depending on the scale of change. Thus, it is important to note the conditions for which the constraints are valid. Especially, when studying long-term changes (the typical situation for life cycle assessments), processes should not be excluded from further considerations because of constraints that only apply in the short term. As the short term per definition does not involve capacity changes, many more production factors are constrained in the short term, but this is irrelevant when considering long-term changes.

Constraints that are long-term enough to limit current investments, and which would therefore normally be accepted to modify the assumption of full elasticity of supply, may still be questioned if their nature is not absolute, as is the case with political constraints and market entry restrictions. For example, the production of ecological foods cannot react immediately to a change in consumer demand due to the time it takes to convert the production facilities to ecological production. In such instances, it would still be reasonable to include the expected delayed effect as part of the consequences of this change in demand. Also, the effects of a decision may be indirect, via the political signal that it sends. For example, a constraint on a specific “green” product may be overcome, for example through political intervention or because a private company takes up the challenge as a result of a consistent unsatisfied demand for this product. Likewise, a consumer boycott of a particular product may be followed up by political action or “voluntary” changes in company behaviour that limits the production beyond the effects of the boycott itself. Since such indirect effects may be controversial and difficult to predict and quantify, it may be preferable to include them in separate scenarios. It should also be taken into account that such indirect effects are often “one-time-only” effects, for example political intervention that shifts a constraint from one level to another. After adjusting to the intervention, the situation finds a new equilibrium at the new level of the constraint.

As a default, if no information is available on constraints, it is advisable to assume that there are none. Unjustified exclusion of suppliers is thereby avoided. If all suppliers to a specific market segment are constrained, or if one or more production factors are not fully elastic, the long-term demand elasticity of the marginal consumers must be estimated and the change followed forward (downstream) in the lifecycle. Identifiable long-term constraints that are regarded as questionable should be analysed in separate scenarios.

If only some suppliers to a specific market segment are constrained, the demand will shift to the unconstrained suppliers. Among the unconstrained suppliers/technologies, some will be more sensitive to a change in demand than others. Capacity adjustments are typically decided on the basis of long-term competitiveness as determined by the expected production costs per unit over long-term. The distinction between constraints and costs is not completely sharp, since some constraints may be translated into additional costs and some costs may be regarded as prohibitive and therefore in practice function as constraints. However, if not taken too strictly, the distinction is useful for practical decision-making. Also the definition of costs itself is not sharp, since concerns for flexibility (as a concern for future costs), environmental costs and other externalities (as proxies for future liabilities), whether monetarised or not, may enter the decision-making process.

Thus, the most sensitive suppliers/technologies are determined from the production costs, while taking into account constraints and non-monetarised costs as perceived by those who decide about the change in capacity (long-term) or capacity utilisation (short-term). The important point is to model as closely as possible the actual decision making context.

As a default, if data cannot be obtained, it may be assumed that the technology affected by a change in demand is the *most* competitive, and that this is the modern technology, except in a decreasing market and for short-term decisions where the affected technology is the *least* competitive, which can be assumed to be the oldest applied technology. With respect to geographical location, it can be assumed that competitiveness is determined by the cost structure of the most important production factor (labour costs for labour intensive products, else energy and raw material costs). When comparing labour costs, local differences in productivity and labour skills should be taken into account.

Consequences when unit processes have multiple products

Identifying how unit processes with more than one product output changes as a consequence of a decision follows logically from the above described more general case. In this section, the particular issues of distinguishing between determining and dependent co-products and of following the downstream consequences of co-products will be described.

A first important distinction is between combined and joint production. In *combined production* the output volumes of the co-products can be independently varied, while in *joint production* the relative output volume of the co-products is fixed. When the output volumes can be independently varied, the co-producing unit process can be sub-divided in separate unit processes for each co-product, each describing only the part of the co-producing unit process that changes with a change in output of that specific co-product. This can also be expressed in terms of the contribution of each co-product to that physical parameter which is the limiting parameter for the co-production function, for example weight or volume in different situations of combined transport. Thus, the modelling of combined production involves only the internal working of the co-producing unit process and needs no further special treatment.

For *joint production*, it is necessary to distinguish between determining and dependent co-products. When the output of the co-products cannot be independently varied, a change in demand for one of the co-products may or may not lead to an increase in the production volume of the co-producing process. This depends on whether the co-product in question is determining for the production volume or not. A *determining co-product* is a joint product (a product from joint production) for which a change in demand will affect the production volume of the co-producing unit process. The procedure described in the previous sections had exactly the purpose of identifying which processes change as a consequence of changes in demand, so it is obvious that when this procedure identifies a co-producing unit process as one that changes, it has at the same time identified the co-product under study as being a determining co-product. The determining co-product(s) then constitutes a constraint on the production volume of the other co-products.

The *overall* production volume of a co-producing process is typically determined by the combined revenue from *all* the co-products, since production of an additional unit will be profitable as long as the total marginal revenue exceeds or equals the marginal production costs. As a starting point, this also implies that *any* change in revenue for *any* co-product may affect the production volume. Thus, to identify a joint product as determining, it is sufficient to document that a change in demand for the joint product leads to a change in revenue for the co-producing process.

However, if there is an alternative production route for a co-product, and under the default assumption in LCA and IOA that suppliers are price-takers, the long-term marginal production cost of the alternative production route for the co-product constitutes a constraint on its price. As long as the long-term market price of a joint product, and thus its contribution to the overall revenue of the co-producing process, is determined by its alternative production route, a change in demand for this co-product will not lead to a change in its (long-term) price and there will be no change in its contribution to the overall (long-term) revenue of the co-producing process. Thus, unless there are co-products from the unit process that have no alternative production routes, *there will be a maximum of one determining co-product from each co-producing unit process*.

If more than one co-product appears to be determining, the following conditions may be helpful in identifying which of the co-products are determining. To be the determining co-product, a joint product, or a combination of joint products in which the co-product takes part, shall simultaneously fulfil these two conditions:

i) It shall provide an economic revenue that exceeds the net marginal cost of changing the production volume.
ii) It shall have a *larger* market trend (relative change in overall production volume) than any other joint product or combination of joint products that fulfil the first condition (taking into account the relative outputs of the co-products). The reason for this is that the joint product (or combination) with the largest market trend provides a constraint on the ability of the other joint products to influence the production volume of the co-producing process. Note that within a combination of joint products, it is the co-product with the *smallest* market trend that is determining, since this co-product provides a constraint on the ability of the combination to influence the production volume.

Example: Given two co-products A and B with alternative production costs of 100 and 50 per simultaneous produced amount, respectively, the first condition is fulfilled by both products if the co-producing activity has a net marginal production cost of lower than 50 for the combined amount of A+B. In this case, the revenue from the co-product with the largest market trend will cover the cost of the other co-product, and thus determine the production volume. If the co-producing activity has a net marginal production cost between 50 and 100, co-product A will be the determining product, because it is the only product that meets the first condition. If the co-producing activity has a net marginal production cost between 100 and 150, both products need to be combined to fulfil the first condition. In a competitive market, the co-product with the largest market trend will be sold at the price of the alternative production cost, while the co-product with the smallest market trend will be sold at the lowest price possible in order to clear the market. Since the price of this co-product cannot be lowered further without bringing the revenue below the marginal costs, this co-product provides a constraint on the production and is thus the determining co-product.

Condition ii) above implies that if more than one joint product or combination of joint products fulfil condition i), then only that joint product or combination which has the relatively largest change in overall demand (market trend) is actually determining. This again emphasises that as long as alternative production routes exist for the joint products, there is only one of the joint products that can be determining for the production volume at any given moment. It follows from the conditions above that the determining co-product is not necessarily the co-product that yields the largest revenue to the process (although this will often be the case), and that the determining co-product is not necessarily the co-product that is having the largest increase (or decrease) in overall production volume. It should be obvious that the two conditions above, and thus the identification of the determining co-product, may change over time, depending on location and the scale of change. Thus, it is always important to note the preconditions under which a given co-product has been identified as determining.

The special situation where there is more than one joint product that has no alternative production route, and therefore more than one determining product, will be dealt with further below. First, we shall deal with the modelling implications in the most common situation with one determining co-product.

First, it should be obvious that the production volume of the co-producing process changes with the demand for the determining co-product. This follows logically from the definition of the determining co-product. This change then implies that also more of the dependent co-products (which may also be called *by-products*) will be produced.

Secondly, it shall be investigated how this additional output of dependent co-products affect other downstream unit processes and markets. Figure 1 illustrates these unit processes and the concepts of split-off point and point of displacement. The *split-off point* is the point where a dependent co-product leaves the processing route of the determining co-product. The *point of displacement* is the point where the dependent co-product is able to displace another product. All unit processes between these two points are called *intermediate treatments*. While it is always relevant to determine the split-off point, it is only relevant to determine a point of displacement when the dependent co-product is utilised fully in other processes and actually displaces other products there. In Figure 1, just one dependent co-product is shown, but in practice there may be any number of co-products, which can each be treated separately with the same procedures.

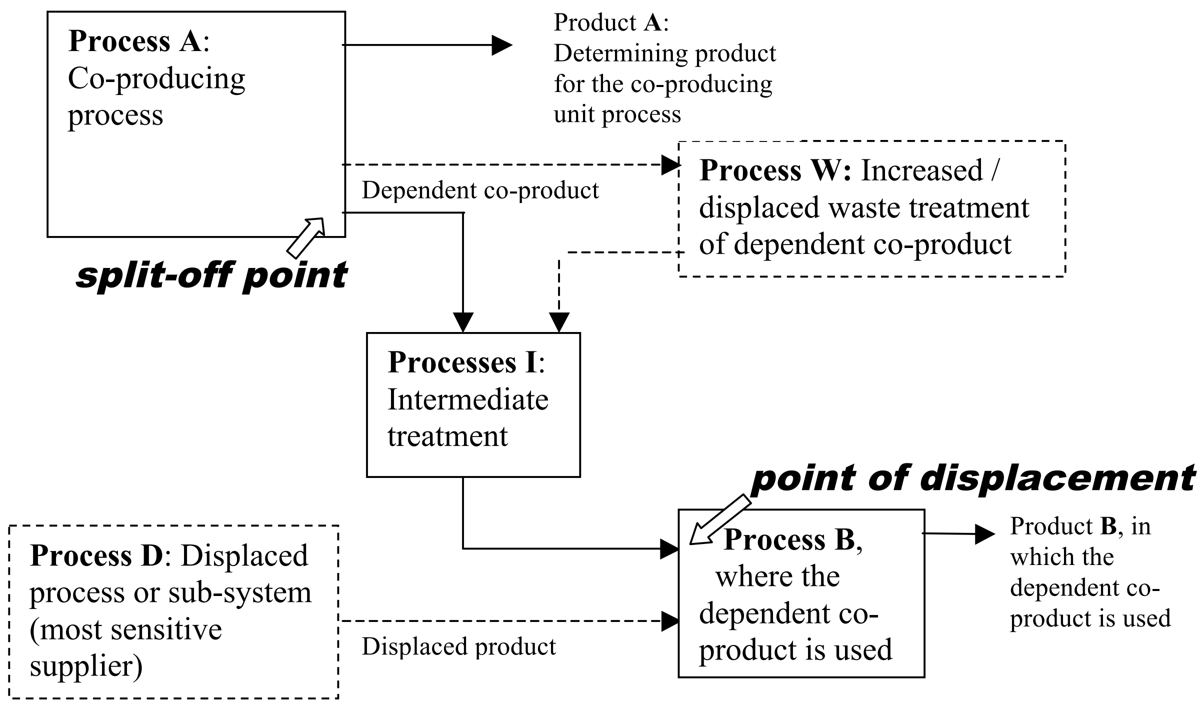

Figure 1. The unit processes that can be affected by changes in demands for co-products.

Which of the unit processes in Figure 1 are affected by a change in demand for either co-product depends on whether the dependent co-product is fully utilised or not.

If the dependent co-product is fully utilised, process W (the waste treatment) is not affected, but both the volume of intermediate treatment (I) and the amount of product which can be displaced (D) are affected by the additional amount of dependent co-product available, which follows from the change in production volume in the co-producing process, which is finally determined by the change in demand for product A. The volume of process B is not affected since it receives the same amount of product (more from process A+I and exactly the same amount less from process D). However, if the dependent co-product after treatment is different in non-market properties from the product it displaces, this difference must be included in the product system of A, in parallel to what was described for other differences in non-market properties in the section on market delimitation. A change in volume of process B, resulting from an increase in demand for product B, will in this situation not be able to influence processes A+I, since these processes are determined exclusively by the demand for product A. Process B therefore needs to be supplied exclusively from process D, which will also be the process identified as the affected process by the procedure described in the previous sections.

If the dependent co-product is *not* fully utilised, this implies that some of it goes to waste treatment, process W. In this situation, an additional amount of the dependent co-product would fully go to waste, simply increasing the amount going to waste treatment. Since the additional amount available cannot influence the demand for product B, there is no additional displacement of process D. On the contrary, an additional demand for product B would result in an increased use of the product from I (the intermediate treatment) and a displacement of the waste treatment of the dependent co-product. Another way of saying this is that in this situation, process I is that supplier to process B, which is most sensitive to a change in demand for product B, and would be the process identified as the affected process by the procedure described in the previous sections.

The two situations described above and their consequences for the modelling can be summarized as shown in Table 1.

Table 1. The situation-dependency of the affected processes. The nomenclature refers to the processes in Figure 1. ΔB signifies the difference in the lifecycle of product B caused by any differences in non-market properties of the outputs from I relative to the product of D.

	Processes affected by a change in demand for product A	Processes affected by a change in demand for product B
Dependent co-product fully utilised	A + I – D + ΔB	D + B
Dependent co-product is *not* fully utilised	A + W	I – W + B

When there is more than one determining product for a process, which happens when there is more than one product output without an alternative production route, the simple modelling described above will not result in a single-product process. Having dealt with any dependent co-products as described above, the following additional operations are required to deal with the determining products.

For joint products that *do not* have any relevant alternative production routes, their prices will adjust so that all the joint products have the same normalised market trend, since only then the markets will be cleared. In this situation, still assuming full elasticity of the entire co-producing activity, 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 margin of the joint production. This is equivalent to the result of an economic partitioning (allocation) of the co-producing process.

However, in a pure economic partitioning of the joint production, two further chains of consequences are ignored, which have to be included in a consequential model:

- Since the change in the co-producing process only partly satisfies the demand that gave rise to the change in its output, the missing supply must be obtained by a reduction in use of the product in its marginal application. Thus, this reduction in marginal use must be added as an input to the modelled system.
- Since the co-producing process is not partitioned, but only scaled to the change in demand, it is still a multi-product process, and the output of the other joint products thus increases proportionally to the induced change in the co-producing process. The additional outputs of any dependent co-products can be dealt with as for the simple situation above, but the output of the other determining co-products influence their further downstream lifecycles, including their consumption and disposal phases, and thus require the inclusion of the processes affected.

A cascade of by-products occurs when the displaced processes also have multiple products. This requires then that the co-products of the displaced process are also analysed and modelled according to the above procedures. If this leads again to another process with multiple products, one might fear that this analysis would have to continue without end. However, the number of possible processes involved is limited since for each time the procedure is iterated, both the economic value and the volume of the displaced processes tend to decrease, because in each iteration the displaced product is the determining co-product of the displaced process and therefore typically of higher value (and often also larger in quantity) than the dependent co-products which go on to the next iteration.

The above described procedures for dealing with multi-product processes has in LCA terminology been called *system expansion* or the *substitution* method. It was originally presented by Stone (1984) for use in IOA where it has become known as the *by-product technology model*. For practical purposes the results of the by-product technology model is strictly identical to the more well-known, more widely used, but less transparent *commodity technology model* (Suh et al. 2009).

To be used in life cycle calculations, each unit process dataset must have one and only one output. In LCA and IOA databases and software, the by-product technology model (substitution; system expansion) can be simply implemented by moving the output of the dependent by-products from being outputs of the co-producing process to be negative inputs of this process. Since intermediate treatment processes are typically regarded as service providing processes to co-producing process, in parallel to waste treatment processes, the intermediate treatment processes are themselves inputs to the co-producing process and the dependent co-products are therefore in practice dependent co-products of these intermediate treatment processes. In the situation with multiple determining products, the co-producing unit process must be duplicated into the same number of processes as there are determining products, since the described procedures must be performed for each of the determining products separately, reflecting the consequences of an increased demand for each product separately.

Any implementation of the by-product technology model can be validated numerically by checking any of the mass, energy, material and/or economic balances, since all of these balances shall be preserved during the transformations. As a positive output equals a negative input, the simple moving of the dependent co-products from positive outputs to negative inputs obviously preserves the balances. Since all originally balanced unit processes are maintained intact (no partitioning), and simply scaled to accommodate the required change in product output, there is no way these unit processes can become unbalanced, except by error. Since the product system is a simple aggregate of these balanced unit processes, the same applies for the resulting product system. To maintain mass balances correct, it is important to note that inputs of treatment services for wastes and by-products have negative mass flows (the mass of the treated waste), while having a positive economic product flow.

Consequences for the functional unit and reference flows

In principle, the output of any unit process in a product system can be applied as a functional unit. Thus, if the procedures in the section “Market delimitation” are applied consistently to all unit processes in the product system, there are no further procedures necessary for describing the functional unit and the reference flows. The functional unit is simply defined in terms of the obligatory product properties on the investigated market, and the reference flows are the specific product flows for each of the product alternatives on this market.

For consequential modelling, the *size* of the functional unit is not arbitrary, but should reflect the extent of the consequences of the decisions studied. This is particularly important when studying decisions involving the entire market of a major product or process, for example studies dealing with the entire waste handling system of a region or studies dealing with legislation or standards for an entire sector, while for small decisions, where the consequences can be assumed linearly related to the size of the change, the precise size of the functional unit will be less important.

In defining a product, it may be necessary to include the complementary products that are used together with the product, but which may not be part of the original product definition. An obvious complementary product is packaging, but also additional products needed for maintenance, replacements, waste treatment, or recycling may need to be added.

Goedkoop et al. (1998) suggests that for some goods it may be necessary to define the functional unit in terms of average customer behaviour (such as “average transport behaviour during one year” for a study of different work-related transport modes or “average diapering behaviour” for a study of disposable versus reusable diapers) to avoid neglecting differences in performance such as that implied by the “rebound effect.”

Rebound effects are the derived changes in production and consumption when the implementation of an improvement liberates or binds a scarce production or consumption factor, such as:

- Money (when the improvement is more or less costly than the current technology).
- Time (when the improvement is more or less time consuming than the current technology).
- Space (when the improvement takes up more or less space than the current technology).
- Technology (when the improvement affects the availability of specific technologies or raw materials).

Examples and procedures for including rebound effects in LCA and IOA are provided in Weidema (2008) and Zamagni et al. (2008).

It is an often used, but seldom explicitly stated, boundary condition in LCA and IOA that the overall productivity of society, that is, the annual GDP or GEP, and the overall societal rate of growth is exogenously determined and not a consequence of the specific decisions studied. Without this boundary condition, the consequences of any specific decision could be infinite, if, for example, an improvement in productivity was reinvested in further improvements etc. However, this boundary condition can be an unreasonable constraint on an analysis of activities that have exactly the aim to increase the overall productivity of society, especially investments in education, research, and development activities in relation to societal infrastructure. The consequences of such investments are by nature long-term, and may occur at very different points in time, have significant signal effects, and may bind other decisions and thus have a cascading effect. To model their consequences beg even more for the use of forecasting and quasi-dynamic models, than LCAs of other types of decisions, and it would be reasonable then also to measure the influence on the GDP over time, taking into account the possible multiplier effects, and to use an appropriate discount rate to compare the net present value of the different options.

Environmental properties may be included among the properties included in the functional unit. However, since the very purpose of LCA is to study the environmental impacts of the products, it is not meaningful to state in advance that the studied products should have such general properties as ”environment-friendly” or ”non-toxic.” If environmental properties are included as obligatory, they must be expressed as specific properties, like ”the barley must be from ecological farms”, so that it is possible to judge - prior to the life cycle study - whether a product has the required property.

5. Present limitations of consequential modelling

The main uncertainty in consequential modelling arises from the standard assumption of full elasticity in the long term and the assumptions on long-term market boundaries and constraints. Large uncertainty is general to any model that relies on long-term forecasting. Especially those market boundaries and constraints that are not physical but rather political have large uncertainties. The use of scenarios with different assumptions and transparent reporting appears as the only viable approach. To refrain from modelling the future does not appear to be a solution, since we would then not be able to obtain an answer to the question posed.

The main limitation for applying consequential modelling in practice is that LCA databases that support this type of modelling are not currently available. However, work is currently undertaken to remove this limitation.

6. Research & development lines

In the short term (3-5 years) there is a need to develop standard LCA databases with data for consequential modelling, with identified market boundaries and explicit cost structures of technologies.

In the mid term (5-10 years) there is a need to improve long-term economic forecasting techniques, to reduce the scenario uncertainty. The modelling of investment decisions and changes in supply and demand, including rebound effects, using equilibrium and econometric models and learning curves. The increasing conceptual complexity of such modelling also requires the development of procedural and communication tools. See also Zamagni et al. (2008).

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