Project no.037075
Project acronym: *CALCAS*
Co-ordination Action for innovation in Life-Cycle Analysis for Sustainability

Instrument: Co-ordination Action
Thematic Priority: Sustainable Development Global Change and Ecosystem

Guidelines for application of deepened and broadened LCA

Due date of deliverable: January 2009
Actual submission date: July 2009

Start date of the project: 1st September 2006 Duration: 30 months

Organisation name of lead contractor for this deliverable
ENEA, The Italian National Agency on new Technologies, Energy and the Environment

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Guidelines for application of deepened and broadened LCA

Deliverable D18 of work package 5 of the CALCAS project

Authors

Bo Pedersen Weidema
2.-0 LCA consultants

Tomas Ekvall
Swedish Environmental Research Institute (IVL)

Reinout Heijungs
Institute of Environmental Science, Leiden University (CML)

Contents

Introduction

CALCAS is the EU 6th Framework **C**o-ordination **A**ction for innovation in **L**ife-**C**ycle **A**nalysis for **S**ustainability[1]. It is aimed at identifying short-term, mid-term and long-term research lines on how to achieve a substantial efficacy increase in supporting sustainability decisions, going beyond the shortcomings and limitations of current LCA[2]. Its general objective, starting out by the ISO-LCA[3], is to develop a broader scientific framework with the following features:

- improvement of reliability and usability of ISO-LCA;
- "deepening" of the present models and tools to improve their applicability in different contexts while increasing their reliability and usability;
- "broadening" the LCA scope by better incorporating sustainability aspects and linking to neighbouring models, to improve their significance;
- "leaping forward" by a revision/enrichment of foundations, through the crossing with other disciplines for sustainability evaluation.

CALCAS workprogramme has been developed along three main lines:

1. Science framework, which includes:
   - critical analysis of the present LCA scientific framework, in relation to the more general discipline of sustainability science and modelling
   - detailed state-of-the-art of LCA applications, with an identification of the most relevant development lines;
   - SWOT analysis of the most promising tools and models for broadening and deepening LCA-methodologies;
   - a survey of existing training programmes characterised by life cycle thinking and identification of ways to promote and assist the incorporation of life cycle thinking in academic curricula and research.
2. Analysis of user needs (four categories: Industry, Government, Consumers and NGOs, Research organisations) and of LCA in relation with sustainability governance.
3. Linking the previous two lines in order to specify programmes for focused scientific development and to identify main sustainability research strategy and research lines.

All this matter has been elaborated, processed and discussed in different documents and workshops, achieving the general result of defining a single unitary logical "structure" for Life Cycle Sustainability Analysis – LCSA, as Scientific Framework including all mechanisms relevant in sustainability assessment, but to be filled at different levels of detail in order to meet the needs of three main applications areas:

- *micro* or product-oriented systems, with limited modifications/effects on space, market, time etc. Their main characteristics are: low variability; low complexity; low uncertainty; good knowledge of data and models. Main expressed needs: standardisation; simplicity; user friendliness; etc.

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[1] See Annex 1 for a short description including all deliverables and other information or: www.calcasproject.net

[2] These have different nature: externalities (economic and social costs), mechanisms (rebound, behaviour, price effects), handling time ((quasi-)dynamic, steady-state), space differentiation (spatially differentiated or spatially independent), etc.

[3] In CALCAS we adopted the convention to call ISO-LCA the Life Cycle Assessment as standardised by the ISO 14040 and 14044 norms.

- *meso* systems, with relevant effects on other systems and on time and space. Their main characteristics are: low variability; high complexity; average uncertainty; availability of enough reliable models and data; main needs: reliability; prevalence of analytical methods over procedural methods or quantitative vs. qualitative; involvement of stakeholders; rebound effects; sensitivity analysis; etc.
- *macro* or economy-wide systems, with low reversibility, high penetration and diffusion capacity in all domains and with relevant effects on all levels. They are characterised by: high variability; high complexity; high uncertainty; many lacks of knowledge and data; main needs: completeness – all possibilities, interactions and mechanisms considered – involvement of experts; combination of procedural and analytical methods; heuristic approach by improvement of learning systems; "upgrading" system; etc.

For each of these application areas, different methods and models (or their combination) can be identified as appropriate; indeed, a "one-size-fits-all" solution is not practicable, but, at the same time, we need an integration framework, on one hand, to reduce complexity and, on the other, to clarify the simplification choices which have been made in the integrative analysis. The framework must be used in such a way that its structure is able to incorporate knowledge from all domains relevant to sustainable development, using a more or less specified value system" (Huppes and Ishikava, 2009). Moreover a single unitary framework is very helpful to identify a coherent way to link micro analysis (where it is possible to implement a very detailed model, using the ISO LCA) to the macro level where, indeed, most of the sustainability questions reside.

Starting from this rationale, CALCAS develops articulated research lines, with different levels of complexity and difficulty, and proposes short, mid and long term objectives. At the same time CALCAS gives also practical indications to strengthen European LCA networking, to implement training plans for educational organisations and provides a more technical contribution on "Consequential LCA" and "Hybrid approaches combining IOA and LCA".

These two topics are presently the most addressed lines of development which try to go beyond the ISO standard, towards a more complete sustainability concept; indeed, they are related to the "broadening" and "deepening" questions of the LCA, well described in D15 and D20, which refer to the general perspective of the LCA developments.

In this regard, the present deliverable D18 has a more practical objective: it makes available the contributions of three of the most recognised experts in the field of consequential LCA and hybrid approaches, and provides practitioners with information on the main principles and guidelines on how to apply these approaches. It takes into account also the achievements of two parallel analyses (review on LCA scientific literature - D7 - and SWOT analysis of LCA supporting models and tools – D10), the results of the CALCAS workshops and the ongoing research activities, with particular attention to UNEP-SETAC Life Cycle Initiative and the European Platform on LCA, where the questions about Consequential LCA are extensively dealt with.

Bo Pedersen Weidema is the main author of the two chapters on "Consequential LCA" and "Hybrid approaches combining IOA and LCA". Tomas Ekvall and Reinout Heijungs are both co-authors and referees respectively of the topics consequential and hybrid approaches. ENEA (Roberto Buonamici) was in charge of the introduction, Annex 1 and of the general editing.

1. CONSEQUENTIAL LCA

1.1. 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 1.3 we discuss the application areas relative to attributional modelling. The main part of the chapter is the guidelines in section 1.4. We end with a discussion of present limitations in section 1.5 and some research proposals in section 1.6.

1.2. 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.

1.3. 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.

1.4. Guideline

1.4.1. 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[4] and expanded. The first procedure is the central one, and the following two can be seen as logical consequences of the first.

[4] 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.

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

1.4.2. 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 instead 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

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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.

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 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.

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.

1.4.3. 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.

1.4.4. 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.

1.4.5. 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.

1.4.6. 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.

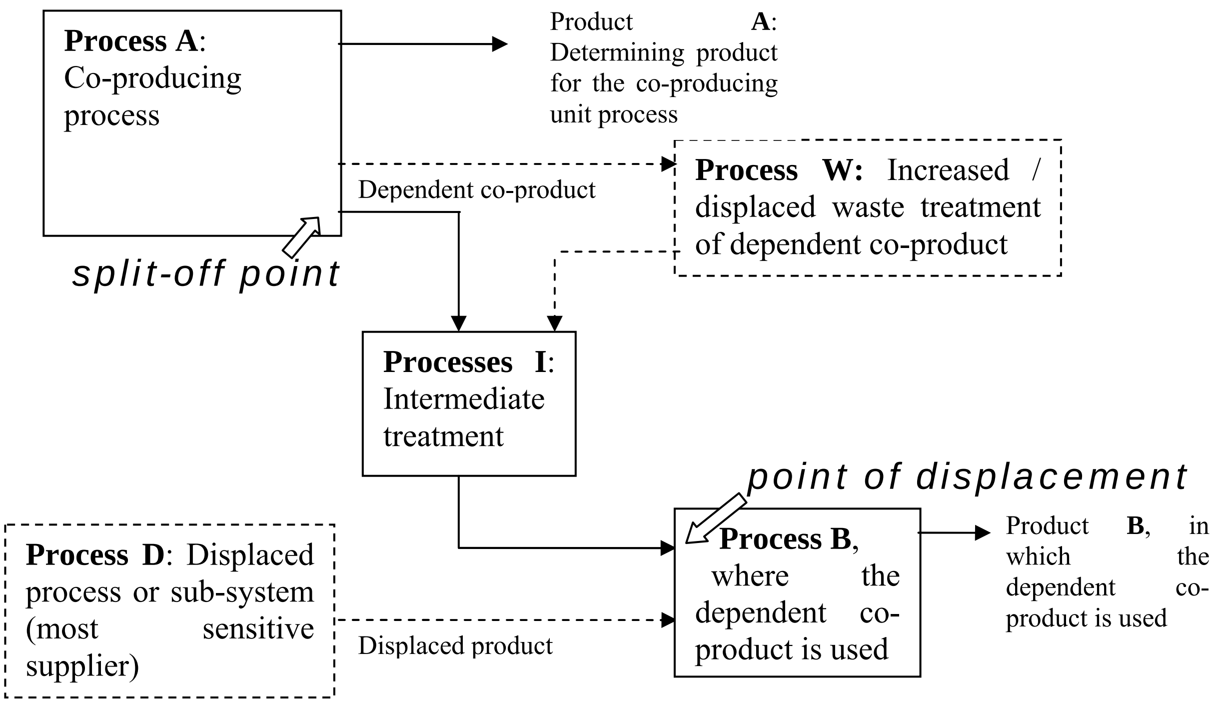

Figure 1 - The unit processes that can be affected by changes in demands for co-products.

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.

1.4.7. 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.

1.5. 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.

1.6. 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).

References

Curran M A, Mann M, Norris G. (2002). Report on the International Workshop on Electricity Data for Life Cycle Inventories. Cincinnati: US Environmental Protection Agency <http://www.epa.gov/nrmrl/pubs/600r02041/600r02041.pdf>

Ekvall T, Tillman A-M, Molander S. 2005. Normative ethics and methodology for life cycle assessment. Journal of Cleaner Production 13(13-14):1225-1234.

Friscknecht R. (1998). Life cycle inventory analysis for decision-making. Scope-dependent inventory system models and context-specific joint product allocation. Zürich: ESU-services. (PhD thesis, Swiss Federal Institute of Technology Zürich).

Goedkoop M J, te Riele H, van Halen C, Rommens P. (1998). Product service combinations. Pp. 125-128 in Proceedings of the 3rd International Conference on Ecobalance, Tsukuba 1998.11.25-27.

Mattsson N, Unger T, Ekvall T. (2001). Marginal effects in a dynamic system – The case of the Nordic power system. Presented to the International Workshop on Electricity Data for Life Cycle Inventories, Cincinnati, 2001.10.23-25.

Stone R. (1984). Balancing the National Accounts: The Adjustment of Initial Estimates; A Neglected Stage in Measurement. Pp. 191-212 in Ingham & Ulph (eds.): Demand, Equilibrium and Trade. New York: St Martin's Press.

Suh S., Weidema B P, Schmidt J H. (2009). Generalized Calculation for Allocation in LCA. Manuscript submitted for Journal of Industrial Ecology.

Tillman A-M. (1998). Significance of decision making for LCA methodology. Key-note lecture at the 8th Annual Meeting of SETAC-Europe, Bordeaux, 1998.04.14-18.

Weidema B P. (2003). Market information in life cycle assessment. Copenhagen: Danish Environmental Protection Agency. (Environmental Project no. 863). <http://www2.mst.dk/Udgiv/publications/2003/87-7972-991-6/pdf/87-7972-992-4.pdf>

Weidema B P. (2008). Rebound effects of sustainable production. Presentation to the "Sustainable Consumption and Production" session of the conference "Bridging the Gap; Responding to Environmental Change - From Words to Deeds", Portorož, Slovenia, 2008.05.14-16. <http://www.lca-net.com/files/rebound.pdf>

Weidema B P, Wesnæs M, Hermansen J, Kristensen T, Halberg N, Eder P, Delgado L. (2008). Environmental improvement potentials of meat and dairy products. Sevilla: Institute for Prospective Technological Studies. (EUR 23491 EN). <http://ipts.jrc.ec.europa.eu/publications/pub.cfm?id=1721>

Zamagni A, Buttol P, Porta PL, Buonamici R, Masoni P, Guinée J, Heijungs R, Ekvall T, Bersani R, Bieńkowska A, Pretato U. (2008) Critical review of the current research needs and limitations related to ISO-LCA practice. Deliverable D7 of Work Package 5 of the CALCAS project. <http://fr1.estis.net/sites/calcas/default.asp?site=calcas&page_id=E2669B0F-9DB7-4D1E-95B0-407BC7949030>

2. HYBRID APPROACHES COMBINING IOA AND LCA

2.1. Introduction

This chapter presents the topic of IO-based LCA and hybrid 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 Reinout Heijungs (Leiden University) 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 2.3 we discuss the main strengths and weaknesses of the different methods. This leads to the guidelines of section 2.4, in the form of a number of recommendations and practical issues. We end with some research proposals in section 2.5.

2.2. Definitions and short descriptions

"Hybrid" basically means the combination of two otherwise distinct approaches. It is therefore used in many different contexts and care should be exercised when using the term. Preferably, a more precise term should be applied. In the context of LCA and IOA, hybrid is used in at least two meanings: *hybrid units*, that are the combination of physical and monetary units for different columns and rows in the same table, and *hybrid data*, that is the combination of process level data and industry level input-output data in the same database. We will deal with both of these meanings, but the focus of this chapter is on the latter.

Input-output (IO) is also a somewhat ambiguous term. It basically refers to a table or matrix (we use here the term table, since any table can be understood as a matrix[5]) where the rows and columns represents either activities or products as inputs or outputs of activities. *Activities*, which can refer to sectors, industries, processes, unit processes, etc., can moreover refer to the production of goods and services, to the consumption of these, and to the processing of waste. Thus, some examples of activities are "production of high-density polyethylene bags", "power plants", "banking", "chemicals production", "storage of radio-active waste". On the other hand, we have *products*, which can refer to commodities, goods, services, wastes, intermediate flows, etc. Thus, some examples of products are "high-density polyethylene bags", "electricity", "financial services", "chemicals" and "radio-active waste".

Two types of input-output tables are of interest here: Supply-Use tables (also known as Make-Use tables) and Direct Requirements tables. The term IO table is often used to signify the latter.

Supply-use tables are, as the name indicates, divided in two, the supply table and the use table. Both tables have activities on one axis and products on the other. The supply table stores data on the supply of products from each activity, and the use table stores data on the use of products by each

[5] Matrix notation is very commonly used to present input-output economics. However, for an introductory text like the present, matrix notation would be an unnecessary complication for some readers, not made up for by an equivalent improvement in readability by readers familiar with matrix notation. All calculations using either or both data types can be performed with or without matrix calculation, although matrix calculation of course immensely helpful in practice.

activity. Together, the two tables can be interpreted as providing the production function of an activity, that is, what production factors (inputs) are required to produce the outputs of an activity. This is illustrated in Figure 2. Supply-use tables are used by national authorities to accumulate and balance enterprise reported data on supplies and use of products, as basis for deriving national economic indicators such as the GDP. The transpose of the supply table is sometimes referred to as a *make table*.

Direct requirements tables have either activities or products on both axes and are derived from the supply-use tables through simple mathematical operations (see description in the below guideline). By convention, rows always indicate supplies or suppliers, while columns indicate use or users. An *activity-by-activity* table stores data on the supply (output) required from each activity as input to each of the other activities in order for them to produce their output, while a *product-by-product* table stores data on the products (supplies) required (used) to produce other product outputs.

Supply and use tables	Activity
Supply of products	**V'**
Use of products	**U**

Direct requirement table	Products used
Products supplied	**A**

Figure 2 - Supply-use and product-by-product direct requirements tables, in which one column represents a production function for an activity or a product, respectively. When presented in this way, the use table is - by convention - named U, the supply table is named V'., and the direct requirements table is named A.

An activity in a supply-use table, as illustrated in Figure 2, often has more than one product output. In contrast, each row and column in a product-by-product direct requirements table represents only one product. In LCA terms, we can say that the *columns in a supply-use table represent "unallocated" multi-product unit process datasets*, while the *columns in a product-by-product direct requirements table represent "allocated" single-product unit process datasets*. In this context, the term product-by-product may be confusing, since the columns still represents an activity, namely the abstract, artificially constructed single product activity, so that the term "product" for the columns merely signifies that the activities each have only single product output. The confusion is enhanced by the somewhat loose way in which some practitioners use product names to indicate activities or the other way around. Leontief (1936) for instance has classes like "agriculture", "flour and milling products", "canning and preserving", "bread and bakery products", and so on.

Input-Output analysis (IOA) was developed by the U.S. economist W.W. Leontief in the 1940's and onwards. He constructed detailed direct requirements tables of the U.S. economy, based on the industry reporting to Federal authorities, and used these to analyse the change in outputs required from each activity to produce an output of a product for final consumption. This linear model of the economy inspired many other studies and won Leontief the Nobel Prize in 1973.

Life Cycle Assessment (LCA) developed from the engineering analysis of cumulative energy requirements in the 1960's and early 1970's, although it was not until the early 1990's that the term LCA obtained its current meaning. Due to the relative isolation of the economic and engineering disciplines, IOA and LCA developed in parallel, without much interaction until the late 1990's.

Some pioneering IOA studies (for an overview, see Miller & Blair 1985) can be said to be *Input-output based LCIs* or *Environmentally extended monetary IOAs*, typically focusing on one specific environmental parameter, such as energy resources. For such studies, the monetary supply-use table is extended by information on the parameter(s) of interest for each of the included activities.

Physical IOA was introduced by Ayres & Kneese (1969), applying the physical mass-balancing principle to the IO structure. In fact, Leontief's first paper (1936) starts with physical IOA. Later, Leontief moved to monetary IOA. Ayres & Kneese took up physical IOA and added the mass balance to that.

A traditional LCI unit process, either multi-product or single-product, can be stored in the same format as an IO activity, and vice versa. Both data types can therefore be stored in the same database, and both can be used in the same life cycle calculations. This is utilised in hybrid analysis, in which two approaches can be distinguished: Tiered and integrated analysis, the latter also being known as embedded analysis.

Tiered hybrid analysis is adding a separate IO table to provide upstream inputs to a table of process level data, see Figure 3. In this approach, some duplication of activities occurs, since the activities represented in the process level table are also included in the IO data.

Tiered hybrid direct requirement table	Products used	Products used
Products supplied	Process direct requirement table	
Products supplied		IO table

Embedded hybrid direct requirement table	Products used	Products used
Products supplied	Process direct requirement table	
Products supplied		Residual IO table

Figure 3 - Illustration of two approaches to hybrid analysis: To the left, a tiered hybrid table, where the self-contained product-by-product IO part provides inputs to the process-level part, but where the process-level part does not deliver inputs to the IO part. To the right, an integrated or embedded hybrid table, where the scaled-up process level data are subtracted from the data for the product-by-product IO table they belong to, to derive residual IO data, and where the two types of data provide inputs to each other. Note that we have also here chosen to represent the process-based LCA table in a product-by-product format, yet referring to it as a process table.

Integrated or embedded hybrid analysis is using a database where the process level data are embedded into the IO data, leaving only the residual of each IO activity after subtraction of the embedded process level data. The process level data and the residual IO data are fully integrated, exchanging inputs both ways, and the resulting database is as representative of the entire economy as the original IO table, just at a higher level of detail.

2.3. Application dependency and present limitations of the methods

Physical and/or monetary units: If we assume an LCA context which includes physical, social and economic impacts, it is an obvious limitation to use only monetary units to model physical flows, as in Input-output based LCI or Environmentally extended monetary IOA, just as it is an obvious limitation to use only physical data to model social and economic impacts. However, the data availability is often determining for what type of analysis is performed. IO tables are much more readily available in monetary units than in physical units, just as a mass balance may be easier to establish than a monetary balance at the process level. When available, physical data are often less uncertain than monetary data (Miller & Blair 1985), and certainly more stable over time. However, service transactions do often not have a physical component, and tend therefore to be overlooked in a purely physical model. Because the two data sources complement each other, an analysis that combines both monetary and physical data will always be preferable. Some LCA databases and software are only able to calculate with one property or unit for each flow, which implies that a mass balance and a monetary balance for the same activities or products can only be performed by duplicating the tables, which is more cumbersome and implies additional probability of creating errors.

Limitations in process level data: Physical process level data are often incomplete, because the collection procedure involves many separate physical flows, some of which may be small and even unknown to the operators of the activity. Although each of these flows may be small, the sum of such missing flows may be significant, and accumulated over the tiers in a product system the missing part of the product system may be larger than the part accounted for. Availability of data may also vary significantly between different activities, resulting in inconsistencies in the way environmental data are reported. For example, a specific toxic emission may be available for the metal working industry, while a much larger emission of the same substance emitted from the chemical industry is unknown. When summing up over the product system, it appears as if the largest problem occurs in the metal working industry. The mentioned limitations are obviously less severe for analyses where the upstream activities constitute a minor part of the total system to be analysed. In all other cases, it is preferable if the missing parts of the process level data can be completed by IO data.

Limitations in IO data: The primary data reported from the enterprises are aggregated by the national statistical agencies, partly to maintain confidentiality of the individual enterprise data, but also simply to limit the size of the resulting tables. For many applications of IO data, for example to construct the national accounts, detail in presentation is not a crucial issue, while consistency of classifications across time and across geographical areas are more in focus. The aggregation makes the data less useful, more uncertain, for use in IOA and LCA. For such purposes, some statistical agencies provide less aggregated data, closer to the original sources. Some of the IO data are not directly measured, but indirectly estimated. The resulting uncertainty may be large if the data are to be used in detailed analyses of specific products. Emission data are typically not consistently available at the level of IO activities, but are calculated from statistical data on for example fuel inputs, using emission factors based on estimates of the composition of inputs, combustion conditions, abatement technologies, etc. This implies that emissions data for IO activities are less detailed than for process level data and often limited to the general (air) emissions for which international reporting requirements exist to UNFCCC, the EU NEC Directive 2001/81/EC, the Convention on Long-Range Transboundary Air Pollution, etc. The mentioned limitations are less severe when the data are used in studies at the societal level, but can be very misleading if applied to very specific products, where a combination of IO data with the more detailed process level data is preferable.

Tiered and/or integrated analysis: In a tiered analysis, the activities represented in the process level part of the table are also included in the IO data part. This duplication of activities does not necessarily lead to double-counting, as long as the table is not used to represent the full economy, but it does imply that the same activity is modelled with less precision upstream than in the "foreground" processes represented by the process level table. In other words, the detailed data provided at the process level is not utilised in the upstream modelling of the same activity. This also implies that the IO table remains the same, even when better information becomes available at the process level. In integrated hybrid analysis, an improvement in the process level data applies equally to all instances of this activity, irrespectively of where in the life cycle it occurs, and as more process level data become available, the part of the table constituted by residual IO data becomes smaller and smaller. However, integrated analysis has higher requirements on data quality, expertise, and resources. Integrated analysis is therefore most relevant when creating LCI databases that can be used by many users and for many analyses.

2.4. Guidelines and recommendations for application

This section describes rules for good practice in EIO-LCA and hybrid LCA. It touches a large variety of subjects, and should be considered more as providing a description of activities to be done than as a set of bullet points.

2.4.1. The balancing principle

For each activity, the law of conservation of mass and energy applies. This implies that the mass and energy in and out of each activity is the same, when taking into account changes in stocks. Only for activities involving nuclear reactions these balances interact. This is also true for each element. Thus, separate mass balances, energy balances and elementary balances apply to all activities except those involving nuclear reactions. Likewise, although there is no "law of conservation of money", a monetary balance also applies to each activity, expressed in the so-called *accounting equation,* which is the foundation for the double-entry bookkeeping system. At the level of products, a similar balancing principle applies, namely that all products used, must also be produced (or vice versa), taking into account changes in stocks.

What is accounted for in the core part of an IO table is the supply and use of intermediate products. If adding imported products to the supply, and exported products and final consumption to the use, the IO table can be balanced per product. To balance the supply and use of an activity, non-product inputs and outputs must also be accounted for. The nature of non-product inputs and outputs are quite different between monetary and physical accounting.

In a monetary IO table, the difference between the value of the outputs (revenue) of an activity, and the value of the inputs of intermediate products (including investments) to this activity, is the expenditures on primary production factors. These can be divided in *labour costs* (wages and other remunerations), *net taxes* (taxes minus subsidies), *net operating surplus* (entrepreneur's income or profit), and *rent* (payment to resource owners). In national accounting practice, rent is included with the net operating surplus and the payments to the primary production factors including investments are together called *value added*, although in formal terms neither investments nor rent are part of the value added by an activity. In national accounting, the value added of an activity is the same as its contribution to the gross domestic product (GDP).

In an IO table in mass units, the difference between the mass of the products of an activity and the mass of the inputs of intermediate products to this activity, is made up by inputs of natural resources, inputs of wastes from other activities, minus net additions to stock, minus outputs of wastes, and minus emissions. The same applies for an energy balance.

The balance per product in the monetary IO table requires that each product is provided in the same kind of values in the supply and the use table. Since this is not necessarily the case, one or more *valuation tables* are added to the right of the supply table in Figure 4, providing the necessary translation between the values of the supply table and the values of the use table. By nature, the original data for a supply table are given in *producer's prices*, while the original data for a use table are given in *purchaser's prices*. The difference is *trade and transport* margins, that is, the cost of the services of wholesalers, retailers and transports. Because trade and transport margins differ not only from product to product but also between users of the same product, a table expressed in producer's prices is more homogeneous than one in purchaser's prices. An even more homogeneous table is obtained if also *product taxes and subsidies* are eliminated from the prices. The resulting price is known as the *basic price*. It is common practice to express the supply table in basic price, and place the trade and transport margins and the product taxes and subsidies per transaction in one or more valuation tables to the right of the supply table. In publication, these tables may be aggregated into single columns.

Before transforming a supply-use table to a product-by-product direct requirements table, it is normal practice to express also the use table in basic prices, by subtracting the valuation tables from the use table, adding the trade and transport margins, aggregated per activity, as inputs from the activities supplying the trade and transport services, and placing the product taxes and subsidies in a separate row below the core table. These taxes and subsidies belong to the value added, but are not included when value added is calculated at basic price.

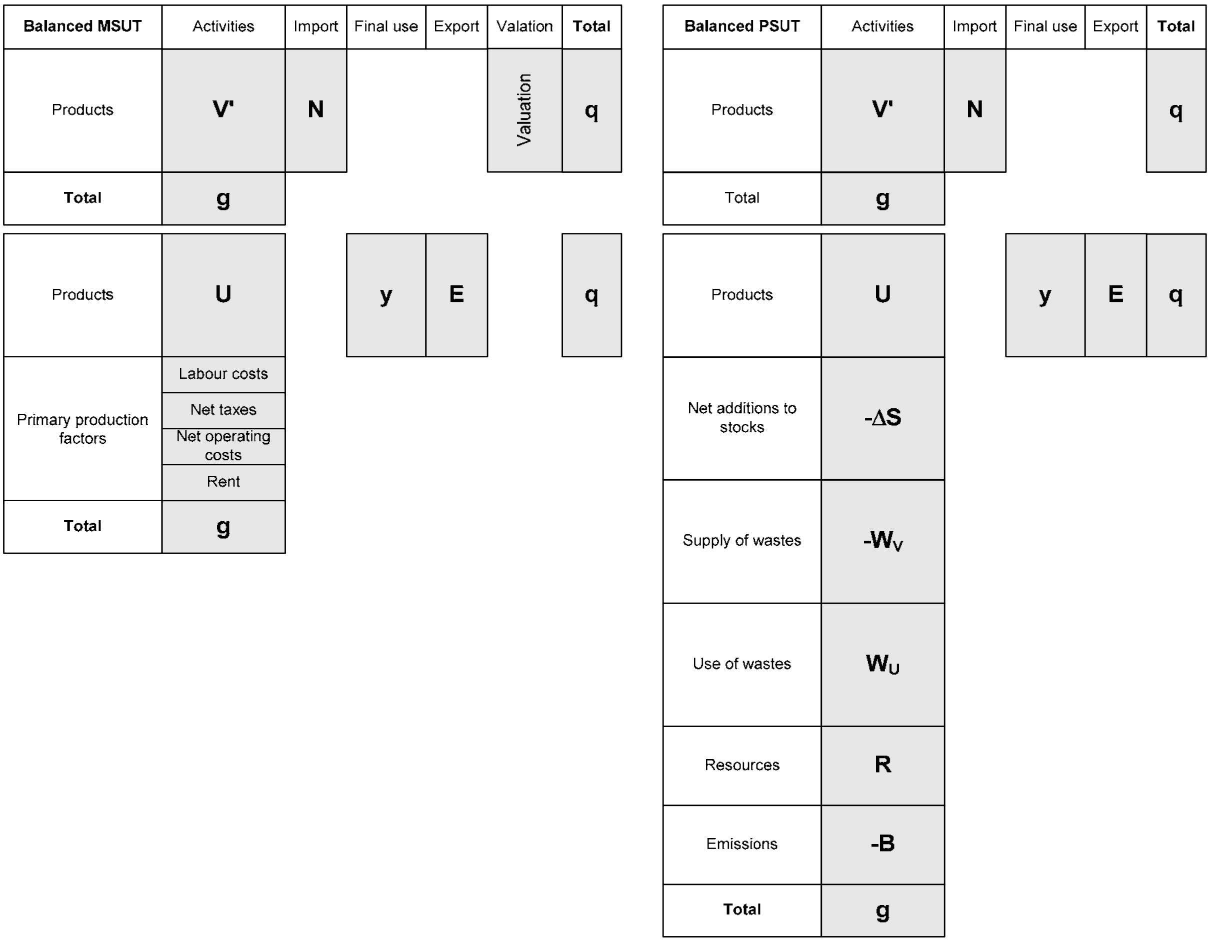

Figure 4 Monetary and physical supply-use tables and the additional tables needed to balance them.

An alternative to the use of a valuation table is to introduce a set of market activities, one for each product, as part of the core supply-use table, see Figure 5. Each market activity uses the corresponding industry product in basic prices and supplies the same product in *average* purchaser’s prices. The difference comes from the inputs from the trade and transport service industries, and the taxes less subsidies, which in this approach are added to the products at the market. If different users pay different prices for the same market product, the difference to the average trade and transport margins must be added directly to the using activity as a (positive or negative) input from the trade and transport service industries. With this approach, the original supply table can be maintained in purchaser’s prices, thus closer to the original statistical data. The tables can still be balanced per product, because each product is provided in the same valuation in the supply and the use table: Industry products are valued in basic prices and market products are valued in purchaser's prices.

Balanced MSUT	Industries	Markets	Import	Final use	Export
Industry products	**Supply** table in basic prices		Import CIF		
Market products		**Market supply** in purchaser's price			
Industry products		**Use** table in basic prices			
Market products	**Use table** in purchaser's price			Final use in purchaser's price	Export in purchaser's price
Primary inputs	Value added at basic prices	Product taxes less subsidies			

Figure 5 - A balanced monetary supply use table using market activities instead of valuation tables.

In a physical IO table, where price valuation is not of concern, the concept of market activities may still be of interest since market activities can be used to model product losses during transport and trade. By assigning a negative mass flow to the product of the waste treatment services, the market activity for the treatment of a specific waste may be applied to distribute the physical amount of this waste over the different waste treatment services, a more disaggregated modelling of waste treatment scenarios can be integrated directly in the core supply-use table, eliminating the need for the two satellite tables for waste in Figure 4.

2.4.2. Hybrid units

The advantage of using the same unit, either monetary or physical, for all exchanges between activities in a table is that the table can then be balanced per activity. This is an important validation tool, and ensures consistency and completeness of the tables. A table in mixed units, that is, where the outputs of different activities have different units, can only be balanced per product, not per activity.

However, a table in hybrid units has other advantages, namely that each product can be expressed in its "natural" unit, that is, the unit which best describes the main function of the product. This reduces the uncertainty of the data. For example, the natural (SI) unit for an energy carrier is Joule. Any other unit (kg, m^3, Euro) would have a higher variability between different suppliers of the same energy carrier, as seen from the perspective of the customer.

To obtain the advantages of a table in hybrid units, while maintaining the option to balance the table per activity, it is necessary to express each flow in terms of its properties in different units of interest, price in monetary units, energy content in energy units, dry mass, water content, and elementary contents in mass units. The balancing algorithm will then be able to use the same property for all flows for each balance. If the software used for the analysis does not support multiple properties of each flow, an alternative approach is to store multiple tables; one hybrid table and one additional table for each property that is to be balanced.

2.4.3. Uncertainty in IO data

At the basic level, monetary IO data are collected and reported by each single enterprise. In some cases, reporting is done at a level below the enterprise, known as Kind-of-Activity-Units (KAUs). These units are intended to be more homogeneous than the enterprise and therefore to reduce the problem of multiple products from one activity. The division in KAUs is equivalent to the subdivision of an activity used to avoid issues of co-production in LCA. The subdivision in KAUs may vary greatly from country to country, which is to some extent also reflected in the share of by-products reported in supply-use tables for different countries. In a country with a good division in KAUs, by-products will typically make up 3-5% of the total product output, while values of 10-15% are often seen for countries relying on data at the enterprise level only. A problem with KAU reporting is that it may underestimate activities that are common for the whole enterprise, that is, unless specifically required, the data from the sum of the KAUs may not add up to the data of the enterprise, and these data gaps then have to be dealt with later. Even when KAUs are not used for reporting, the concept can still be used by the statistical agency to disaggregate enterprise data, for example by separating out a transport supplying activity from a manufacturing industry and placing this part in the transport industry. Effectively, this can only be done by applying the same assumptions about input structures of the industries as applied in dealing with co-products (see later about these transformations).

The coverage of data collection for monetary IO tables varies from 100% to smaller samples, especially for small enterprises. Also, not all data are necessarily collected every year, and some data are therefore interpolated for years where data are not collected. The data are also sometimes collected at a higher level of product aggregation than used in the published tables. When the collected data arrive at the statistical agencies, data from several activities are aggregated. In this process of aggregation, the variation of the sample may be established, but this may not be done and at least this uncertainty is not reported specifically when data are made publicly available. Secondly, when necessary, data are disaggregated to the level of product detail used by the statistical agency, and missing data are estimated and distributed to balance the tables. The balancing principle is applied to identify implausible data and errors, and to adjust data from the least credible sources. This balancing exercise involves subjective assessments of data quality, so that the data with the least quality are more likely to be adjusted. While these data quality assessments and the additional uncertainty they introduce could be documented and estimated, this is either not done or at least not externally reported. Weidema et al. (2005) estimated the aggregation uncertainty of IO data, based on the variation between the same tables at different levels of aggregation, and found a very clear, close to linear, increase in variation as more commodities are aggregated. The largest aspect of uncertainty can also be expressed as allocation uncertainty, because the total values are often known with higher precision than the values for each activity (for example, the financial balance sheet of a company is closely audited, while the classification of each item in the balance sheet is not; the total extraction of natural resources may be closely monitored, while the use in each activity is not). For a study of a specific product, these allocation and aggregation uncertainties may be significant, while it is less important for studies at the level of the whole economy.

It would be preferable if statistical agencies in general provided actual uncertainty estimates for each of their data points, but even just such data from one country, based on a detailed analysis of uncertainty in the actual generation of an IO table, would be helpful to establish better uncertainty estimates of IO data in general. The estimates for each data-point in the IO tables may be propagated in the IOA or LCA using the same uncertainty propagation techniques as for process level data.

Physical IO data are typically based on physical information in resource statistics, production statistics, and trade statistics (imports and exports). The same aggregation uncertainties apply and the same lack of reporting of the uncertainty of the statistical data points can be found as for monetary data.

2.4.4. Adapting monetary IO data for LCA

The IO tables published by national statistical agencies do not include the *consumption stage* as an activity, but as a column outside of the activity table. In LCA, the consumption stage is an activity in parallel to any other activity, with inputs of products and natural resources, and outputs of wastes and emissions. The product outputs of the consumption stage are needs fulfillments such as meals, leisure, communication, safety and security, etc. To prepare an IO table for use in LCA, the final use column should be integrated into the core activity part of the table, and modelled as an activity with product outputs. It may be further sub-divided to reflect the interaction between different products and activities in the households, for example that cars and transport fuels are used together in the household activity 'car driving', which may then provide its part of its product to the household activity 'shopping', which again can deliver part of its product to 'meal preparation'. In this way, the structure of the household activities can be modelled and improvement options investigated in more detail. In a few countries, the statistical agencies produce *household satellite accounts*, in which the household production is modelled in parallel to the industry production in the core IO table. When this is done, the productive time use of the households is typically monetised, so that the household processes also have imputed labour costs that contribute to the household value added, which can then be added to the GDP to produce the *Gross Economic Product* (GEP), which reflects the value of the full societal production.

In the IO tables published by national statistical agencies, capital formation (investments, infrastructure, capital goods) are not included in the core activity part of the table. Product supplies that go into capital formation are represented by a separate column in final consumption, outside of the activity table, and the depreciation of the investment expenditures is represented by a separate 'use of fixed capital' row outside of the activity table. In LCA, the capital goods are seen as part of the production function of each activity, in the same way as other product inputs. To prepare an IO table for use in LCA, the 'capital formation' column and 'use of fixed capital' row should be integrated into the core activity part of the table. This is done by applying an *investment table*, which has the same format as the use table and provides information on the distribution of the 'capital formation' on activities. If an investment table is not available from the national statistical agency, it may be constructed by extrapolation from another country's investment table, normalised to the total output of each activity. Since the incorporation the 'capital formation' into the core activity part of the IO table represents a specification of the 'use of fixed capital' row under a steady-state-assumption, this row must then be eliminated to avoid double counting of the use. Because the 'use of fixed capital' row is determined from depreciation allowances, its sum is not necessarily equal to the sum of the 'capital formation' column. The incorporation of the 'capital formation' column and the simultaneous elimination of the 'use of fixed capital' row may therefore give rise to small discrepancies between the total inputs and outputs of each activity. These discrepancies must be adjusted in the net operating surplus.

In a physical IO table, the net additions to stock, as represented by the investment table, is also participating as an output in the mass balance of each activity, to match the input of capital goods. To maintain all mass flows of each activity in the same column, it is most convenient simply to include the investment table (in mass units) as a separate table below the core IO table, with a negative sign (representing an output that should be subtracted in the mass balance).

The IO tables published by national statistical agencies reflect the situation in a specific year, for example the specific production of new cars, the emissions from the current fleet (composed of cars of many ages), and the waste treatment of old cars scrapped in this year. In both LCA and IOA modelling, long-lived products are typically represented by steady-state models, for example a car will typically be modelled with the current production technology, the average life time emissions and the current waste treatment technology, all divided by the lifetime of the car. Effectively, this means that the net additions to stock are simply contributing as physical inputs to the waste treatment activities of the current year. A better model would be possible if LCI data were available in forecasted time series, so that the fuel use of the car could be obtained as inputs during its future life time, the waste treatment based on a future waste scenario, and the accompanying emissions placed at their correct point in time. Due to their internal consistency, IO tables are well suited as basis for making consistent forecasts of the entire economy.

2.4.5. Transformation of a supply-use table to a product-by-product direct requirements table

To be used in IOA or LCA calculations, the supply and use table or the direct requirements tables must be invertible, which means it must be square, that is, they must have as many activities as products. Original supply-use tables of national statistical agencies are often rectangular, in the sense that they have more products than activities. Either the activities must be disaggregated, which requires additional information to be meaningful, or several products must be aggregated to the level of an activity, implying the assumption that these products have the same production function. The assignment of products to activities will normally be guided by the correspondence table between the product and the activity classification. For process-level data, the reverse problem may occur that there are more activities than products. In this case, either the products must be disaggregated per activity or several activities that supply the same product must be aggregated.

As the activities in a supply-use table have multiple products (*co-products*), they cannot be used directly for IOA or LCA, since these techniques require that each activity have only one product output. Transforming a supply-use table to a product-by-product direct requirements table can be done in two principally different ways, by *substitution* or by *partitioning*. Substitution is also known in LCA terminology as *system expansion* and in the terminology of IO economics the operation is known as the *by-product technolog*y model. For practical purposes the results of applying the by-product technology model is strictly identical to the more well-known *commodity technology model* (Suh et al. 2009), but since the results of the latter model are less transparent, it will not be further discussed here. Partitioning is also known in LCA terminology as *co-product allocation* and in IO economics the equivalent operation is known as the *industry technology model* because it effectively assumes that all product outputs of an industry activity have the same production function relative to the partitioning parameter. A number of other methods exist, which are all variations of the above.

In the *substitution method*, the co-products are divided in *determining products* and *by-products (dependent products)* and the output of the by-products are assumed to substitute the supply of the same product from the marginal supplier to the market for the by-product. In practice this substitution is modelled by eliminating the by-product output and placing it as a negative input to the same activity. In this way, the monetary, mass and energy balances of the co-producing activity are maintained (from a balancing perspective, a negative input is the same as a positive output), while the negative input leads to a substitution of the supplying activities of this input. This simple substitution procedure requires that each activity has only one determining product, which is not the case when there is more than one product output without an alternative production route. We come back to the more complicated procedure required when there is more than one determining product, after first describing the partitioning method.

In the *partitioning method*, the co-producing activity is simply partitioned into as many activities as there are co-products, each having only one of the co-products as outputs, the output of the others being set to zero, and the remaining entries in each new activity are then scaled by ratio of the new output to the output of the original co-producing activity, expressed in the units of the partitioning parameter. Typically, revenue is used as partitioning parameter, which is often argued to reflect the causal relationship between the size of the activity and its revenue steam, where an increase in the activity can be expected to be proportional to the increase in revenue. When all the product outputs to be partitioned are expressed in the unit of the partitioning parameter, such as is the case in a single-unit supply-use table, it is unnecessary to duplicate the activities, and each column in the direct requirements table can therefore be expressed simply as the market-share-weighted sum of the production functions of the activities supplying the product. It should be noted that the columns in a partitioned direct requirements table cannot be balanced for any other parameter than the one used for the partitioning. For example, if the partitioning is done with revenue as partitioning parameter, then inputs and outputs of mass and energy will not balance. This, in combination with the underlying improbable assumption that all product outputs of an industry activity have the same production function, are the main reason that the partitioning method is generally dissuaded. While still very popular in process level LCAs, partitioning is hardly used for the transformation of IO tables in empirical research (Beutel 2008).

If there is more than one determining product for an activity, the simple substitution described above will not result in a single-product activity. In this situation, the following operations are required to also deal with the multiple determining products. As a first step, the activity is partitioned according to revenue, following the partitioning method above, but without adjusting the outputs of the co-products differently than any other output. Effectively, this is a duplication of the activity, where each of the partitioned activities is scaled to the output of one of the determining products. This reflects the above described causal relationship, which is valid when there are no alternative production routes that determine the price of the products, but without the violation of the balancing principle that follows from artificially adjusting the outputs of the co-products. The resulting partitioned activities are therefore still multi-product activities. The following steps are performed for each of the resulting partitioned activities. As the second step, the product for which the partitioned activity is scaled is increased, so that the partitioned activity now yields the same revenue as the original activity, and the amount of product needed is at the same time added as an input, representing a reduction in use of the partitioned product by the marginal user of this product. This reflects that an increase in demand for the product is only partly met by an increase in the activity. Since the same amount of product is added as input and output, the activity is still balanced. As the third step, the outputs of the other determining products are eliminated by placing them as negative inputs, representing the increased consumption of the marginal consumer of these products, resulting from the increase in the co-producing activity. As for the simple substitution, a negative input is the same as a positive output, so that the monetary, mass and energy balances of the resulting activities are maintained, while the negative input in this case leads to a substitution of the consuming activities of this input, because there are no alternative production routes. Finally, the non-determining products are dealt with as described for the simple substitution situation.

Although national statistical agencies publish direct requirements tables, it can generally be recommended to use instead the original supply-use data and to perform the transformation (substitution or partitioning) yourself, because:

- The operations performed by the statistical agencies to arrive at the direct requirements table are seldom reported in a transparent way, and often the methods deviate more or less from what is described above, especially in terms of the additional efforts that are often made to eliminate negative values; efforts that may in fact corrupt basically sound data. Some agencies do not publish product-by-product tables, but instead industry-by-industry tables, which are less relevant for LCA.
- Supply-use data are published with less delay and usually more frequently and with more product detail than the corresponding direct requirements table.
- When starting from the supply-use data, you can perform both of the above transformations, and thereby compare the results of these on the same statistical data basis, which may be relevant for different kinds of analyses.
- When starting from the supply-use data, you can include other data sources obtained for the same activities as in the supply-use table, for example natural resource and energy inputs, waste statistics, emissions data, and work hours, and ensure that these are included in the transformation in exactly the same way as the intermediate input.

2.4.6. *Statistical classifications*

Although UN classification systems exist both for activities and products (ISIC and CPC, respectively), different statistical agencies use different activity and product classifications. Especially the North American Industry Classification System (NAICS) is a widely used activity classification. Correspondence tables exist between many of the classifications, but in case of overlapping categories these do not eliminate the need for manual interaction during translation. Furthermore, all classification systems are regularly being revised, which adds to the work required when combining several tables. And even when statistical agencies follow the same classification, there may be subtle exceptions and differences in interpretations that make an error-free translation difficult. If possible, the original classifications should be maintained when translating, allowing later revisions.

In most cases, it is uncomplicated to assign process level data to activity and product classes. Sometimes, it may be difficult to determine the level of processing that causes a product to move to a different classification, for example how much beneficiation a mined product can receive before it should be classified as a manufactured product. Subtle differences, such as the fact that alumina is a product of the chemical industry, while aluminium is a product of the non-ferrous metals industry, may also cause problems for the uninitiated. Recycling processes are usually integrated with the activities that produce the virgin products, so that the 'Materials recovery' class only covers the collection and possibly some sorting and cleaning.

It may be difficult to determine whether an activity takes place internally in an industry or in a separate industry. For example, some capital goods may be produced within each industry rather than in a separate construction or machinery industry, some waste treatment may take place internally rather than at an external treatment plant, some fuels may be used for transport activities by own lorries rather than in the transport industry. These problems resemble those of recording data at the level of KAUs described above under uncertainty, and should preferably be dealt with in the same way, namely by sub-dividing the activities to produce only one product, identifying the relevant industries in which to place such internal activities. KAU reporting distinguishes own-account production or products for own final use, from products for sale or non-market products (products that are paid via general taxes or similar). From an LCI perspective, these distinctions are irrelevant, since the production functions do not depend on where the product is used or how it is paid for.

A process level LCI database will typically have more activity sub-division than statistical agencies, for example typically all internal heat production that is not a by-product of the manufacturing will be placed in one or a few technically defined activities (and classified under 'Steam and air-conditioning supply'), rather than included in each manufacturing activity, and all agricultural field operations will be recorded separately from the crop production (and classified under 'Support activities for plant production'), disregarding whether these operations are performed by the farmer or by a contractor. The more detailed the subdivision, the more non-monetised internal trade will be recorded.

2.4.7. Geographical resolution

Most IO tables are produced at a national level, but some organisations use these national data to produce more or less standardised versions covering more countries, but still with the national resolution. Some better-know examples are Eurostat, the OECD and GTAP. Some countries, like the USA and Spain, produce sub-national tables covering different regions.

To account for imported products being different than nationally produced, the national tables need to be linked, at least to a Rest-of-World (RoW) table. Since IO-tables are not available for all countries, one of the larger and more detailed tables, such as the one for USA, is often used as a proxy for the RoW table.

Linking tables from different countries is done via import tables, where the import to each national activity is specified on supplying activity in the exporting country. Import tables are constructed by subtracting the imported shares of each element in the use table, based on the ratio of import to domestic supply, as provided per product in the supply table. If more tables are linked, and the share of import from each supplying country is unknown, the linking may be made via a table representing a global trade pool, to which all unspecified exports are supplied, and from which all unspecified imports are drawn.

When the importing table has lower resolution than the exporting table, the imports need to be distributed over the exported products. Without more specific information, the best key to apply is the export column of the exporting country.

Monetary IO tables are usually provided in the current national currency. If two countries with different currencies are linked, the import table must include the exchange rate between the importing country and the exporting county’s currencies. A verifiable exchange rate should be applied, such as the annual averages provided by International Monetary Fund in their International Financial Statistics. Note that while purchase power standards may be relevant when comparing and aggregating impacts, they are *not* relevant when translating direct trade values.

Derived from the supply table in purchaser’s prices, the import table will be expressed in “free-on-board” (FOB) prices, that is, excluding international trade and transport margins. These margins are expressed by the difference to the import values in “cost-insurance-freight” (CIF) prices, as recorded in a ‘CIF/FOB adjustments’ row, and are separately imported from the supplying country or from another country supplying these services. To ensure that the inputs and outputs of these international trade and transport services are included in the assessment, the ‘CIF/FOB adjustments’ row must be linked to the exporting trade and transport industries.

2.4.8. Input-output based LCI (Environmentally extended monetary IOA)

The simplest form in which IO tables can be applied for environmental assessments is to provide an environmental extension to the monetary supply-use table. To maintain all information for each activity in the same column, it is most convenient simply to include the environmental exchanges in separate rows below the core use table.

Data on natural resources are available from resource statistics, and it is usually obvious which extracting activity they are inputs to. Some emissions data are available from national emission registers, and others can be derived by using an emission factor approach. Without detailed activity data, the emissions will typically be limited to those that can be derived from fuel inputs.

Data on social externalities, for example labour rights violations, may also be collected at the level of IO activities, but systematic work in this field is still in its infancy. Some economic externalities, for example direct perverse subsidies, can be derived from the information in the 'taxes less subsidies' row in the primary factor part of the IO tables, while indirect subsidies, for example via trade barriers, are less easy to identify, and have to be derived from other sources. The recording of economic internalities, are obviously the strong point of IO tables, and life cycle costing (LCC) can therefore be performed very simply by using the value added as a costing parameter. This may be further enhanced by the distribution of the primary factors on different income groups, for example through data on work hours performed by persons with different educational levels or from different income groups. With this information, distributional analysis can be performed for the social and economic part of the assessment.

The calculation procedures for an input-output based LCI are identical to those of a process level LCI. The only difference is in the detail of the activities included, and that all transactions between the activities are recorded in monetary rather than physical units.

2.4.9. Constructing physical supply-use tables

A physical supply-use table is constructed by applying data on physical flows of activities and the relation between monetary and physical flows (prices). Product prices and/or data on physical flows may be obtained from production, imports, and export statistics. When combined with resource statistics and emissions data, the mass balancing principle allows building up a supply-use table that matches the monetary supply-use table. For respiration, digestion and combustion processes, it is important to include oxygen and carbon, both as natural resource inputs and in emissions. To avoid the need for water balancing, it is recommended to enter data and perform calculations in dry mass. In this context it should be noted that the digestion of (dry) biomass will give rise to an output of respiratory water, which is therefore – somewhat counterintuitive – to be included in the *dry* matter balance.

The flow for which least data is available is wastes, and waste is therefore mainly estimated as a residual. A separate table for physical outputs of wastes, and a table for input of the wastes to waste treatment and recycling activities complete the physical balance, see Figure 4. The two waste tables balance each other, since all wastes outputs are received as inputs by other (treatment) activities. An alternative to the two separate waste tables is to integrate this information into the core part of the IO table by assigning the waste as a negative mass flow to the product of the waste treatment services.

2.4.10. Tiered hybrid analysis

Having identified missing inputs in process level data that is, inputs for which no process level data are available, these missing inputs can be linked to supplies from the corresponding activity class in the monetary or physical IO table. Since missing process level inputs will typically be known in physical units, linking to a physical IO table will usually be simpler and provide a more precise result. If only a monetary IO table is available, the monetary value of the missing inputs needs to be estimated.

The described procedure can only be used for known missing data, that is, inputs that are known to be missing but for which upstream process level data are not available. However, many inputs are simply unknown, and can only be identified by comparing the process level data to IO data for the closest fitting activity class. By estimating the monetary value of all the intermediate inputs to the activity and comparing this value to the expected sum of intermediate inputs (the value of the output minus the average value added for this kind of activity), an estimate of the unknown missing data can be established. The nature of the unknown missing inputs may be estimated by comparison to the input coefficients of the IO activity, or it may simply be accepted as unknown and linked to an average output of all IO activities.

2.4.11. Constructing an embedded hybrid database

To embed process level data into a supply-use table, the two types of data structures must first be adjusted to match each other. Many of the necessary adjustments have already been described above:

- The integration of valuation table or market activities into the core part of the supply-use table, depending on which of the two methods have been applied for the process level data.
- The integration of final consumption activities into the core part of the IO table.
- The integration of the investment table into the core part of the IO table.
- The assignment of process level data to activity and product classes.
- Constructing a physical IO table in parallel to the monetary.

Some further necessary adjustments are:

- Adjusting the geographical specification of imports in the use table to match that of the process level data. Since process level data typically do not have a geographical import specification, this implies that the embedding should be performed before any geographical specification of imports in the use table.
- Adding to the IO table flows of complementary products, such as packaging, to match the modelling of these flows in the detailed process level data (in a physical IO table, packaging is typically not included with the product flows, and therefore appears to become waste at the producer rather than at the user).
- Checking the mass balances of the process level data to ensure that their quality is adequate for integration. The same concerns and conventions as used when making the physical supply-use table applies to the process level data.
- Adding to the process data the price and production volume data for the geographical area, since these are required to scale up the process level data to the level of the geographical economy of the IO table.
- Adding to the process level database import and export activity datasets for each product, based on trade statistics for the specific geography. These are required for the balancing of the product flows after embedding.

A final issue concerns the non-monetised internal activities that typically have a higher occurrence in the process level LCI database than in the corresponding supply-use table, as mentioned above under statistical classifications (with the example of internal heat production being recorded under ‘Steam and air-conditioning supply’ rather than included in each manufacturing activity). In some cases, like the agricultural services and the purchase of animal feed, the amounts will be included in the supply-use table when supplied by a contractor or by another farmer, but not when supplied by the farmer herself. Since the true values, that is, the total amount of these intermediate products, are better known from the process level LCI data, these values should be used to adjust the supply-use table before integration. Whenever an internal activity is added, the product supply increases, but so does the use of this added product. As price information is often not available for internal processes, prices must be imputed from the costs of the inputs, adding an average amount of added value for the industry in question. The resulting monetisation of internal activities will increase the total monetary output but the total value added remains the same (because the same money “changes hands” more often, but with a proportionally smaller amount of value added between each exchange).

The process based LCI data and the supply-use table will now have the same structure, and the integration can be performed. The integration consists of 5 steps:

- The process level LCI data are scaled up to the level of the geographical production volume.
- The up-scaled LCI data are summed up for each product-activity classification level of the supply-use table, and these aggregated data are subtracted from the corresponding cell content in the supply-use table. The result is a residual for each cell in the supply-use matrix. These may be represented as ‘residual IO activity’ datasets, at this time only using inputs from other ‘residual IO activity’ datasets.
- For each of the products in the up-scaled process LCI database, a monetary and a mass balance at the geographical level is performed, thereby identifying the missing use of each product.
- The missing use is distributed to the residual IO activity datasets, using the size of the activity residuals for the corresponding product group as distribution key, and subtracting the distributed missing use from the corresponding residual data, thereby obtaining a *remaining residual* for each cell in the original use table. The residual IO activity datasets now have the relevant inputs from all other activities.
- The remaining residual, representing input of unspecified products, is redistributed over all non-market activity datasets, using the monetary value of the production output as distribution key. To maintain the balance per activity, the value added of the activities are adjusted accordingly, most simply by subtracting the distributed remaining residual from the net operating surplus of each activity.

Emissions can be added to the residual IO activities, but since the residual activities per definition cannot have any process-specific emissions, emissions can only be added on the basis of emission factors relating to specific inputs, such as fuels. Since fuels are primarily inputs of the specific heat producing activities, it will in most cases only be for this residual heat producing activity that emissions can be meaningfully added. Even when no emissions are added for the residual IO activities, they play a role in increasing the completeness of the life cycle emissions of all products in the database, since they serve as (previously missing) links to other activities that *do* have emissions.

Meaningful waste outputs (or materially specified inputs of waste treatment services) can be added to the residual IO activities based on their mass balances.

2.5. Research & development lines

The research recommendations can be divided into three areas: data, methods and experience.

Data

In the short term (3-5 years) improvements in the process databases are required, so that they can be more easily integrated with the supply use data, implying the use of a recognized process and product classification, adding economic and production volume data, and applying mass and monetary balancing consistently to all activity datasets.

For the mid term (5-10 years), improvements should focus on data availability from statistical agencies. The primary data on physical flows needs to be improved, and the aggregation level in published data kept at the necessary minimum to protect confidentiality. Linking of physical and monetary data and balancing of physical tables should be performed already at the statistical agencies. Statistical agencies should document their estimation procedures better and report on uncertainty, preferably for each cell in the supply-use tables.

Methods

Concerning methods, although the main principles of IO-based and hybrid LCA appears to be clear, there are still many details to be filled in, especially on the harmonization of the two in a tiered or integrated way. Traditional LCA is based on a steady-state, IOA on a 1 year account, with information on capital formation and depreciation. These two different systems should be reconciled. Likewise, process-based LCA is a global network of activities, whereas IOA is a regionally delimited system excluding households and treating imports and exports in an aggregated way.

Experience

Many IOA (including EIOA) and LCA studies have been performed and published. The hybrid approaches have been demonstrated, in most cases using small stylized examples of 5 products with hypothetical data. Application to real case studies should be encouraged, in order to demonstrate the added value of integrated LCA, and to discover more practical issue like how to resolve the mismatch in activity and product classifications, how to obtain the links between physical and monetary data, how to include uncertainty analysis and demonstrating the application of consistent allocation procedures.

References and further reading

Ayres R U, Kneese A V. (1969). Production, consumption, and externalities. American Economic Review 59:282-297.

Beutel J. (2008). Eurostat Manual of Supply, Use and Input-Output Tables. Luxembourg: Office for Official Publications of the European Communities.

Bullard, C.W., Penner, P.S., Pilati, D.A. (1978). Net energy analysis. Handbook for combining process and input-output analysis. Resources and Energy 1:3, 267-313

Cicas, G., Hendrickson, C.T., Horvath, A., Matthews, H.S. (2007). A Regional Version of a US Economic Input-Output Life-Cycle Assessment Model. International Journal of Life Cycle Assessment 12:6, 365-372

Duchin, F. (1992). Industrial input-output analysis: implications for industrial ecology. Proceedings of the National Academy Science USA 89, 851-855

Duchin, F. (2005). Sustainable Consumption of Food: A Framework for Analyzing Scenarios about Changes in Diets. Journal of Industrial Ecology 9:1-2, 99-114

Facanha, C., Horvath, A. (2006). Environmental Assessment of Freight Transportation in the U.S. International Journal of Life Cycle Assessment 11:4, 229-239

Hawkins, T., Hendrickson, C., Higgins, C., Matthews, H.S. (2007). A mixed-unit input-output model for environmental life-cycle assessment and material flow analysis. Environmental Science & Technology 41, 1024-1031

Heijungs, R., Suh, S. (2002). The computational structure of life cycle assessment. Kluwer Academic Publishers, Dordrecht

Heijungs, R., Koning, A. de, Suh, S., Huppes, G. (2006). Toward an Information Tool for Integrated Product Policy: Requirements for Data and Computation. Journal of Industrial Ecology 10:3, 147-158

Hendrickson, C., Horvath, A., Joshi, S., Lave, L. (1998). Economic input-output models for environmental life-cycle assessment. Environmental Science & Technology, A184-191

Hendrickson, C.T., Lave, L.B., Matthews, H.S. (2006). Environmental life cycle assessment of goods and services. An input-output approach. Resources for the Future, Washington.

Huppes, G., Koning, A. de, Suh, S., Heijungs, R., Oers, L. van, Nielsen, P., Guinée, J.B. (2006). Environmental Impacts of Consumption in the European Union: High-Resolution Input-Output Tables with Detailed Environmental Extensions. Journal of Industrial Ecology 10:3, 129-146

Joshi, S. (1999). Product environmental life-cycle assessment using input-output techniques. Journal of Industrial Ecology 3:2-3, 95-120

Junnila, S.I. (2006). Empirical comparison of process and economic input-output life cycle assessment in service industries. Environmental Science & Technology 40, 7070-7076

Koellner, T., Suh, S., Weber, O., Moser, C., Scholz, R.W. (2007). Environmental Impacts of Conventional and Sustainable Investment Funds Compared Using Input-Output Life-Cycle Assessment. Journal of Industrial Ecology 11:3, 41-60

Krishnan, N., Boyd, S., Somani, A., Raoux, S., Clark, D., Dornfeld, D. (2008). A hybrid life cycle inventory of nano-scale semiconductor manufacturing. Environmental Science & Technology 42:8, 3069-3075

Lave, L.B., Cobas-Flores, E., Hendrickson, C.T., McMichael, F.C. (1995). Using input-output analysis to estimate economy-wide discharges. Environmental Science & Technology 29:9, A420-426

Lenzen, M. (2001). Errors in conventional and input-output-based life-cycle inventories. Journal of Industrial Ecology 4:4, 127-148

Lenzen, M. (2002). A guide for compiling inventories in hybrid life-cycle assessments: some Australian results. Journal of Cleaner Production 10, 545-572

Lenzen, M., Treloar, G. (2003). Differential convergence of life-cycle inventories toward upstream production layers. Journal of Industrial Ecology 6:3-4, 137-160

Leontief, W.W. (1936). Quantitative input and output relations in the economic system of the United States. The Review of Economic Statistics XVIII:3, 105-125

Matthews, H.S., Small, M.J. (2001). Extending the boundaries of life-cycle assessment through environmental economic input-output models. Journal of Industrial Ecology 4:3, 7-10

Matthews H.S., Hendrickson C.T. (2002). The Economic and Environmental Implications of Centralized Stock Keeping. Journal of Industrial Ecology 6:2, 71-81

Miller R, Blair P. (1985). Input-Output Analysis: Foundations and Extensions. Englewood Cliffs: Prentice-Hall.

Miller, S.A., Theis, T.L. (2006). Comparison of life-cycle inventory databases. Journal of Industrial Ecology 10:1-2, 133-147

Murray, A., Horvath, A,, Nelson, K.L. (2008). Hybrid life-cycle environmental and cost inventory of sewage sludge treatment and end-us scenarios: a case study from China. Environmental Science & Technology 42, 3163-3169

Nakamura S., Kondo Y. (2002). Input-Output Analysis of Waste Management. Journal of Industrial Ecology 6:1, 39-63

Nijdam, D.S., Wilting, H.C., Goedkoop, M.J., Madsen, J. (2005). Environmental load from Dutch private consumption. How much damage takes place abroad? Journal of Industrial Ecology 9:1/2, 147-168

Norman, J., Charpentier, A.D., Maclean, H.L. (2007). Economic input-output life-cycle assessment of trade between Canada and the United States. Environmental Science & Technology 41:5, 1523-1532

Norris G.A., Della Croce F., Jolliet O. (2002). Energy Burdens of Conventional Wholesale and Retail Portions of Product Life Cycles . Journal of Industrial Ecology 6:2, 59-69

Peters, G. (2007). Efficient Algorithms for Life Cycle Assessment, Input-Output Analysis, and Monte-Carlo Analysis. International Journal of Life Cycle Assessment 12:6, 373-380

Pin, X., Kraines, S. (2001). Environmental input-output models for life-cycle analysis. Environmental and Resource Economics 20, 61-72

Strømann, A.H., Solli, C., Hertwich, E.G. (2006). Hybrid life-cycle assessment of natural gas based fuel chains for transportation. Environmental Science & Technology 40, 2797-2804

Strømman, A.H., Solli, C. (2008). Applying Leontief's Price Model to Estimate Missing Elements in Hybrid Life Cycle Inventories . Journal of Industrial Ecology 12:1, 26-33

Suh, S., Huppes, G. (2002). Missing Inventory Estimation Tool Using Extended Input-Output Analysis. International Journal of Life Cycle Assessment 7:3, 134-140

Suh, S., Lenzen, M., Treloar, G.J., Hondo, H., Horvath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J., Norris, G. (2004). System boundary selection in life-cycle inventories using hybrid approaches. Environmental Science & Technology 38:3, 657-664

Suh, S. (2004). Functions, commodities and environmental impacts in an ecological–economic model. Ecological Economics 48, 451-467

Suh, S. (2005). Developing a sectoral environmental database for input-output analysis: the Comparative Environmental Data Archive of the US. Economic Systems Research 17:4, 449-469

Suh, S., Huppes, G. (2005). Techniques for life cycle inventory of a product. Journal of Cleaner Production 13, 687-697

Suh S., Shinichiro, N. (2007). Five Years in the Area of Input-Output and Hybrid LCA. International Journal of Life Cycle Assessment 12:6, 351-352

Suh, S., Heijungs, R. (2007). Power Series Expansion and Structural Analysis for Life Cycle Assessment. International Journal of Life Cycle Assessment 12:6, 381-390

Suh S., Weidema B P, Schmidt J H. (2009). Generalized Calculation for Allocation in LCA. Manuscript submitted for Journal of Industrial Ecology.

Treloar, G., Love, P.E.D., Crawford, R.H. (2004). Hybrid life-cycle inventory for road construction and use. Journal of Construction Engineering and Management, 43-49

Treloar, G., Love, P.E.D., Faniran, O.O., Iyer-Raniga, U. (2000). A hybrid life cycle assessment method for construction. Construction Management and Economics 18, 5-9

Tukker, A., Eder, P., Suh, S. (2006) Environmental impacts of products. Policy relevant information and data challenges. Journal of Industrial Ecology 10:3, 183-198

Weidema, B.P., Suh, S., Notten, P. (2006). Setting priorities within product-oriented environmental policy. The Danish perspectives. Journal of Industrial Ecology 10:3, 73-87

Weidema B P, Christiansen K, Nielsen A M, Norris G A, Notten P, Suh S, Madsen J. (2005). Prioritisation within the integrated product policy. Environmental project no. 980. Copenhagen: Danish Environmental Protection Agency. <http://www2.mst.dk/Udgiv/publications/2005/87-7614-517-4/pdf/87-7614-518-2.pdf>

Williams, E. (2004). Energy intensity of computer manufacturing: hybrid assessment combining process and economic input-output methods. Environmental Science & Technology 38, 6166-6174

Yoshida, Y., Ishitani, H., Matsuhashi, R., Kudoh, Y., Okuma, H., Morita, K., Koike, A., Kobayashi, O.a (2002). Reliability of LCI considering the uncertainties of energy consumption in input-output analyses. Applied Energy 73, 71-82

ANNEX 1 – CALCAS project

CALCAS aims at identifying research lines on how to achieve a substantial efficacy increase in supporting sustainability (not only environmental) decisions, going beyond the shortcomings and limitations of current Life Cycle Assessment (LCA). Its general objective is to further develop the ISO-LCA[6] into a broader scientific framework, named Life Cycle Sustainability Analysis (LCSA) with the following features:

- improved reliability and usability of ISO-LCA;
- "deepening" of the present model (i.e. adding more mechanisms and/or more sophistications) to improve its applicability in different contexts while increasing its reliability and usability;
- "broadening" the LCA scope by better incorporating sustainability aspects and linking to neighbouring models, to improve their significance;
- "leaping forward" by a revision/enrichment of foundations, through the crossing with other disciplines for sustainability evaluation.

Partners of CALCAS are:

- Ente Nazionale per le Nuove Tecnologie, l'Energia e l'Ambiente (ENEA) Co-ordinator
- Institute of environmental sciences CML, Leiden University. Scientific Co-ordinator
- Swedish Environmental Research Institute (IVL)
- Wuppertal Institute for Climate, Environment and Energy
- Institute for Environment and Sustainability (JRC IES)
- School of Chemical Engineering Analytical Science – University of Manchester
- ARMINES
- Environmental Policy Research Centre (FFU) Frei Universitat Berlin
- Instituto Superior Tecnico, Technical University of Lisbon (IST)
- European Science Foundation (ESF)
- Institut für ökologische Wirtschaftsforschung gGmbH, (IÖW)
- Society of Environmental Toxicology and Chemistry - Europe VZW (SETAC EUROPE)
- Chemistry Innovation (CI)

CALCAS workprogramme has been developed along three main lines, producing a number of deliverables (see Table 12), available for downloading in the project informative web site www.calcasproject.net.

[6] In CALCAS we adopted the convention to call ISO-LCA the Life Cycle Assessment as standardised by the ISO 14040 and 14044 norms.

Table 2 - Work lines, main tasks and principles deliverables of CALCAS project

WORK LINE	MAIN TASKS	DELIVERABLES
Science framework	critical analysis of the present LCA scientific framework, in relation to the more general discipline of sustainability science and modelling	D1 Scope Paper; D15 A scientific framework for LCA
	detailed status of the art of LCA applications, with an identification of the most relevant development lines	D7 Critical review of the current research needs and limitations related to ISO-LCA practice
	SWOT analysis of the most promising tools and models for broadening and deepening LCA-methodologies	D10 SWOT analysis of LCA-supporting models and tools; D17 Options for deepening and broadening LCA
	a survey of existing training programmes characterised by life cycle thinking and identification of ways to promote and assist the incorporation of life cycle thinking in academic curricula and research; networking	D12 Training Implementation Plan on Life Cycle topics for Educational Organizations in Europe; D16 Strengthening European networks on Life Cycle topics – a CALCAS contribution
Analysis of user needs	Analysis of needs of four categories of users: Industry, Government, Consumers and NGOs, Research organisations	D9 Results from survey of demand for life cycle approaches in sustainability decision support: user needs; D11 Practical requirements for sustainability decision making. Summary Report of Workshop LCA and beyond – Science towards sustainability; D19 What LCA options may supply: user assessment
	LCA in relation with sustainability governance	D6 LCA options for sustainable governance assessed; D13 Sustainability governance with new LCA
Leaping forward: Crossing needs and science supply	Improvement of reliability and usability of ISO-LCA	D14 Main R&D lines to improve reliability, significance and usability of the applications of standardised LCA
	Deepening and broadening LCA	D18 Guidelines for application of deepened and broadened LCA
	Definition of new LCA strategies research lines and road map	D20 Blue Paper on Life Cycle Sustainability Analysis (The present document) D22 Research strategy for expanding Life Cycle Sustainability Analysis; (Later)