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Market information in life cycle assessment

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Danish Ministry of the Environment

Contents

Preface

This report was prepared within the Danish LCA methodology and consensus creation project during the period from 1997 to 2003.

The report is one out of five technical reports to be published by the Danish Environmental Protection Agency and dealing with key issues in LCA. The reports were prepared as background literature for a number of guidelines on LCA, planned to be published by the Danish Environmental Protection Agency during the autumn of 2003. The reports present the scientific discussions and documentation for recommendations offered by the guidelines. The reports and guidelines developed within the project are presented in the overview figure below.

A primary objective of the guidelines has been to provide advice and recommendations on key issues in LCA at a more detailed level than offered by general literature, like the ISO-standards, the EDIP reports, the Nordic LCA project and SETAC publications. The guidelines must be regarded as a supplement to and not a substitution for this general literature.

It is, however, important to note that the guidelines were developed during a consensus process involving in reality all major research institutions and consulting firms engaged in the LCA field in Denmark. The advice given in the guidelines may thus be considered to represent what is generally accepted as best practice today in the field of LCA in Denmark.

The development of the guidelines and the technical reports was initiated and supervised by the Danish EPA Ad Hoc Committee on LCA Methodology Issues 1997-2001. The research institutions and consulting firms engaged in the development and consensus process are:

COWI, Consulting Engineers and Planners (Project Management)
Institute for Product Development, the Technical University of Denmark
dk-TEKNIK ENERGY & ENVIRONMENT
The Danish Technological Institute
Carl Bro
The Danish Building Research Institute
DHI - Water and Environment
Danish Toxicology Institute
Rambøll
ECONET
National Environmental Research Institute

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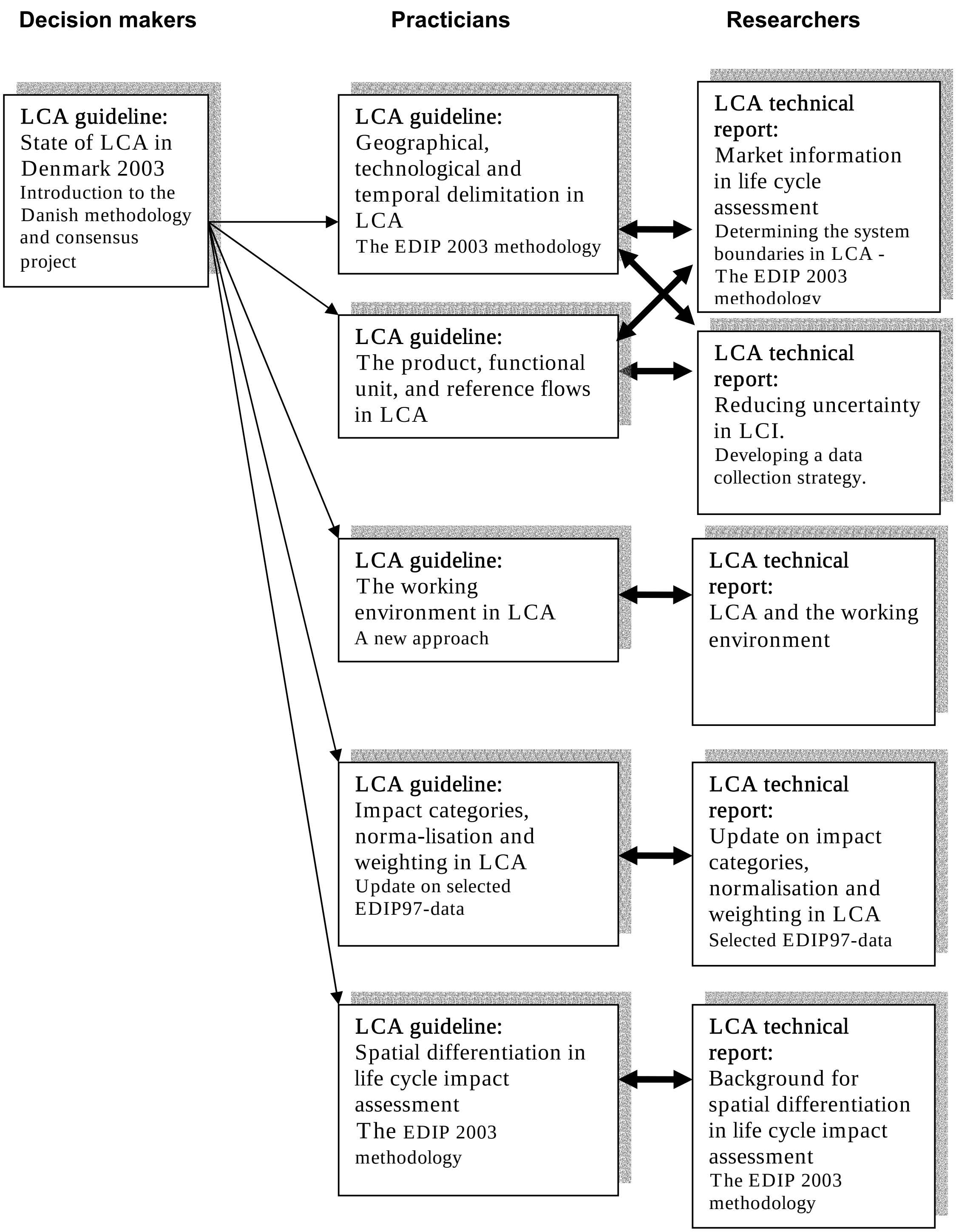
Guidelines and technical reports prepared within the Danish LCA-methodology and consensusproject



1 Introduction[5]

This report provides the background for the two guidelines "The product, functional unit, and reference flows in LCA" (Weidema et al. 2003a) and "Geographical, technological and temporal delimitation in LCA" (Weidema 2003). It provides further documentation of the examples provided in these guidelines, as well as additional examples, further explanatory text, scientific background and reference to earlier methodological guidelines. It also expands on specific issues, which were not found to be of sufficient general interest to merit inclusion in the guidelines.

This report and the two guidelines that it supports, carry two key messages:

1. The fundamental rule to apply in all methodological choices in life cycle assessment is that the data used must reflect as far as possible the processes actually affected ***as a consequence*** of the decision that the specific life cycle assessment is intended to support. Thus, there is a close link between the goal or application area of the life cycle assessment and the methodological choices. This is elaborated in section 1.1.

2. Life cycle assessments, insofar as they deal with comparing potential choices between alternative products, rely heavily on market information, i.e. information on how the market affects the potential choices and how the markets will react to these choices.

Whenever possible, the above understanding has been converted to practical, step-by-step procedures for including market information when:

- defining the functional unit (chapter 3),
- defining the geographical and technological scope (chapter 4),
- handling co-products (chapter 5),
- forecasting data for processes taking place in the future (chapter 6).

For all these elements of the life cycle assessment methodology, the inclusion of market information leads to improvements, which also reduces the uncertainty of life cycle assessment results. While the methodological improvements are described in this report, the consequences for uncertainty are the topic of a separate report: "Reducing uncertainty in LCI. Developing a data collection strategy" (Weidema et al. 2003).

1.1 The relation between application areas and methodology

The methodological elements listed above are fundamentally determined by the temporal and spatial aspects of the studied systems and by the products and interest groups affected. On this basis, six well-defined application areas can be distinguished (see figure 1.1).

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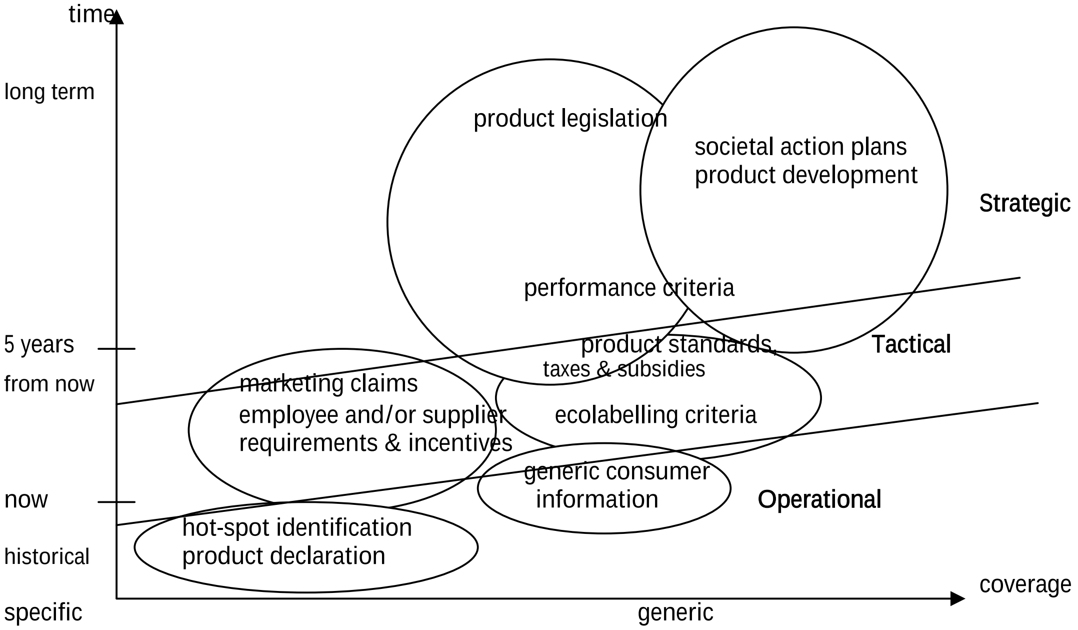
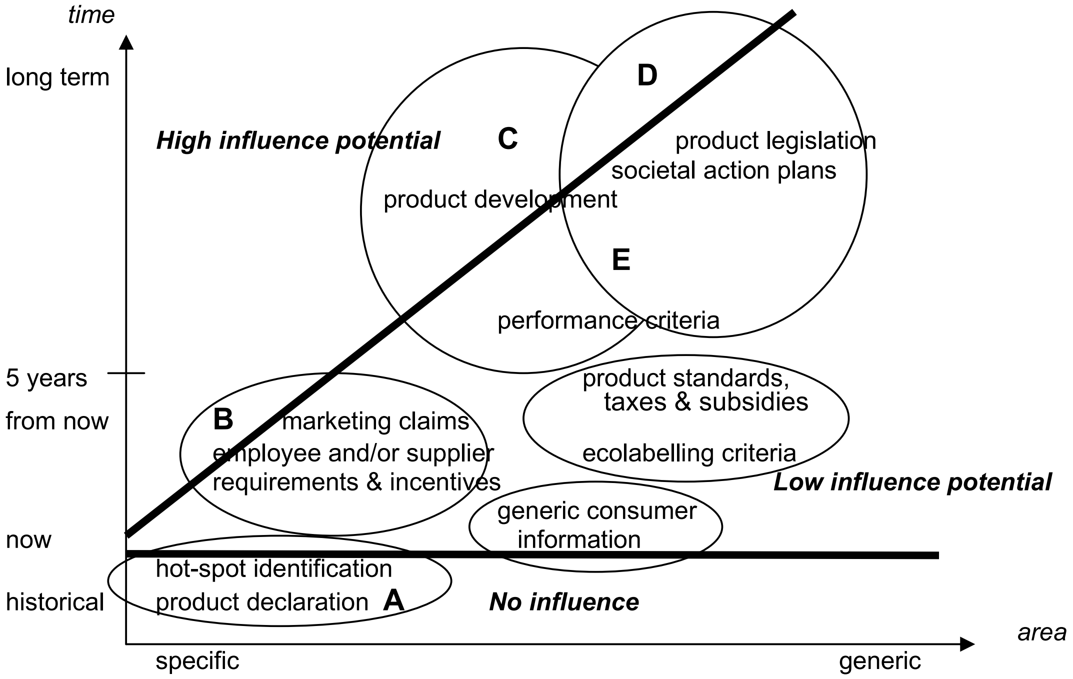
[5] An early version of this introduction was presented to the 3rd International Conference on Ecobalance, Tsukuba 1998.11.25-27 (see Weidema 1998b).

Figure 1.1. The application typology in relation to its determining parameters (from Weidema 1998a).



The decision-maker's potential influence on the different processes in the product systems increases towards the top left of the diagram, i.e. as the decision horizon becomes more long-term and as the decision relates to more specific products and geographical areas. This is further illustrated in figure 1.2. For retrospective studies (area A in figure 1.2), there is no choice to influence. For medium-term, tactical studies, high influence on specific processes throughout the life cycle is limited to studies where the product systems are very well-defined and where the decision-maker already ***at present*** has a high influence on the other actors in the life cycle (illustrated by area B in figure 1.2). Tactical aspects (i.e. contacts to be made in the product chain) may also be part of the considerations in product development, and the more long-term the development, the more ambitious one may be with respect to obtaining influence (area C). Even on a societal level, it may be possible to influence specific choices throughout the life cycle, when the products are relatively well-defined and have well-defined interest groups (including producers and users), and when the time horizon is long enough to allow the necessary regulative and technical infrastructure to be developed (area D). For the rest of the applications (area E in figure 1.2), the products are either too generic (i.e. includes several products or a group of products) or involve too many interest groups to allow a decision-maker to influence specific choices throughout the life cycle.

Figure 1.2. The influence of the decision-maker in relation to the application area



With respect to methodological choices, the most important distinction is that between the ***retro***spective, ***attributional*** life cycle assessments of the accountancy type[6] (typically applied for hot-spot-identification, product declarations and for generic consumer information) and the ***pro***spective ***consequential*** life cycle assessments, which study the environmental consequences of possible (future) changes between alternative product systems (typically applied in product development and in public policy making) (Tillman 1998, 2000). This distinction is further elaborated in section 1.2.

The application areas (as outlined in figure 1.1) affect the methodology in the following ways:

- The functional unit, which delimits which product alternatives can be included in the study, is affected by the time horizon of the study and by the degree of specification of the studied product (specifically defined products and long time horizons allow more alternatives to be included). This point is elaborated in section 1.4 and further in chapter 3.
- The processes to include in the product systems studied are affected by the distinction between attributional and consequential applications (including either those processes which can be associated with the product according to a chosen rule or those which are affected by a product substitution). This is elaborated in section 1.5.

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[6] Also known as status-quo or descriptive LCAs as opposed to the consequential LCAs, which are also known as change-oriented, effect-oriented or comparative (Ekvall 1999). In principle, attributional LCAs may also be performed in an estimated future situation, and consequential LCAs may describe the consequences of a historical decision. We therefore generally use the terms attributional and consequential rather than terms that signal a temporal context.

- Within consequential studies, the technologies to consider and whether to include capital goods, maintenance etc., is affected by the distinctions between small/large and short-term/long-term changes. These distinctions (which are defined in section 1.3) are related to the parameters in figure 1.1, but do not exactly follow the divisions between application areas given there. The way these distinctions affect the technologies to consider is elaborated in section 4.2.
- The method for handling co-products is also affected by the distinction between attributional and consequential applications (attributional applications require economic allocation while consequential applications require system expansion). This is elaborated in section 1.6 and further in chapter 5.
- The methods to use for forecasting future processes is affected by the time horizon and complexity of the studied system (determining whether forecasts should be made by extrapolation, modelling or scenario methods), and by the amount of stakeholders affected (determining whether participatory forecasting is relevant). Furthermore, exploratory and normative forecasting may be relevant for specific applications in product development. This is elaborated in section 1.7 and further in chapter 6.

Thus, for each application area of figure 1.1, we can outline the conditions for the methodological choices to be taken:

- For attributional life cycle assessments:
    - As attributional LCA does not apply to comparison of alternative product systems, the functional unit does not play any important role for the assessment, and may therefore be chosen at will.
    - The processes to include are those that are deemed to contribute to the studied product.
    - Co-products are handled by economic allocation, since attributional LCA does not involve changes, which is a necessary condition for applying the system expansion procedure.

Note that when defining the goal and scope of an attributional LCA, one should be aware whether one intends later to use the results for decision making, in which case it should be carefully considered whether it is necessary and worthwhile to perform an attributional LCA or whether a consequential study is adequate and sufficient. See also the discussion in section 1.2.

- For studies of specific products, affecting specific interest groups on a medium (1-5 years) term (for product declarations, hot-spot-identification, marketing claims, and incentives and requirements for suppliers or employees):
    - The functional unit shall reflect the current products on the market and their obligatory properties (see definition in chapter 2).
    - The processes to include are those that are affected on short or long term by the decision supported by the results of the study (i.e. choosing the product with the market claim instead of the alternatives, following the incentives or fulfilling the supplier/employee requirements instead of continuing status-quo).
    - Co-products are handled by system expansion.
    - Forecasting of processes is done by extrapolation.
- For studies of generic products (product groups) on a medium (1-5 years) term (for generic consumer information, ecolabelling criteria and product standards, taxes and subsidies):

  - The functional unit shall reflect the current products on the market and their obligatory properties (see definition in chapter 2).
  - The processes to include are those affected on short or long term by the decision supported by the results of the study (i.e. choosing a product with the ecolabel instead of the alternatives, changing behaviour following the taxes or subsidies or fulfilling the product standard instead of continuing status-quo).
  - Co-products are handled by system expansion.
  - Forecasting of processes is done by modelling and participatory methods.
- For studies used to support societal action plans, product legislation and generic performance criteria:
  - The functional unit may be broadened to include alternatives assumed relevant under future conditions of availability, price, and product information.
  - The processes to include are those processes, which are affected by the decisions supported by the results of the study (typically large, long-term consequences).
  - Co-products are handled by system expansion.
  - Forecasting of processes is done by modelling and scenario methods.
- For studies used in product development and for enterprise specific performance criteria:
  - The functional unit may be broadened to include more alternatives in all parts of the product chain, when assumed to be controlled by the decision maker and relevant under future conditions.
  - The processes to include are those processes, which are affected by the decisions supported by the results of the study (long-term consequences, small or large).
  - Co-products are handled by system expansion.
  - Forecasting of processes is done by modelling and scenario methods. For processes where a large degree of control is assumed, also exploratory and normative methods may be applied (see chapter 6 for definitions).

Unfortunately, the above recommendations are not in complete accordance with the recommendations from the Dutch methodology project (Guinée et al. 2001), which was carried out simultaneously with the Danish project of which this report is a result. In spite of close agreements on many important basic concepts (see Guinée 1999) we did not succeed in reaching consensus on the specific recommendations to be given in our respective guidelines. The main differences between the guidelines are that the Dutch guideline restricts its recommendations to a baseline situation (applications with small, long-term consequences), and recommends an intentional disregard for market mechanisms and their consequences. In relation to the definition of the functional unit, the latter recommendation implies an assumption that there are no changes in consumer behaviour in relation to product substitutions, such as the so-called “rebound effect”, and that differences in consumer prices do not induce the consumer to spend more or less money on other products. In relation to system delimitation, it implies an assumption that all processes will react to changes in demand in proportion to the revenue obtained for the production (i.e. that relative supply elasticities equals relative prices) without any side-effects, so that the affected technology will be the average of the currently installed technology, and so that co-production does not lead to substitution and may therefore be handled by economic allocation.

The argument for this intentional disregard for market mechanisms is apparently that a full modelling of market mechanisms is not practicable, and that using an incomplete model of market mechanisms may introduce large uncertainties in the modelling. Thus, the Dutch guideline opts for an incomplete description rather than an uncertain description of the markets. In this way, there is an inconsistency between the Dutch recommended methodology and the application area for which it is suggested (consequential studies), as also pointed out by several of the international reviewers (Guinée 1999). In section 2.4 we continue the discussion on the issue of market modelling, and provide further arguments for intentionally ***including*** market mechanisms and their consequences.

1.2 Discussion of attributional versus consequential LCA

The relevance of attributional LCAs has been questioned (Weidema 1998b, Wenzel 1999), because the ultimate goal even of hot-spot-identification and product declarations is to improve the studied systems:

- If an attributional hot-spot-identification identifies a number of improvement options, a consequential assessment is still needed to assess the consequences of implementing the improvements, so one might as well perform a consequential study in the first place.
- If product declarations are used by the customer to make a choice between several products, this choice should ideally be based on the environmental consequences[7] of this choice (i.e. a specific, medium-term, prospective study), not on the historical impact caused by the products[8].
- Likewise, if generic consumer information affects the behaviour of the consumer, this behavioural change should ideally be based on the environmental consequences of this change (i.e. a generic, medium-term, prospective study).

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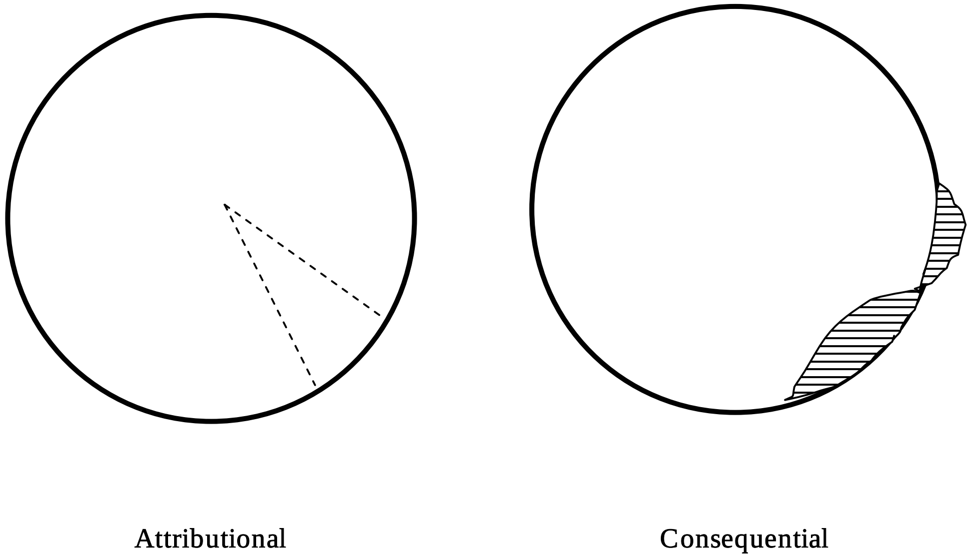
[7] Although Ekvall (2000) and Ekvall et al. (2001a, b) argue that choices could also be based on other premises than environmental consequences, in which case an attributional LCA based on these premises could be relevant (see also the further text in this section).

[8] The issue of product declarations is dealt with in more detail in section 4.7, since the potential ambiguity in the purpose of this application make it useful as a touchstone for methodological debates.

Figure 1.3. The conceptual difference between attributional and consequential LCA. The circles represent the total global environmental exchanges. In the left circle, attributional LCA seeks to cut out the piece with dotted lines that belongs to a specific human activity, e.g. car driving. In the right circle, consequential LCA seeks to capture the change in environmental exchanges that occur as a consequence of adding or removing a specific human activity.



Even a question that appears retrospective at first sight (like “If I look at the world as it is now, what is the environmental contribution of car driving?”, Guinée 1999, p.5) does not appear to have a meaningful answer, except if we reformulate it as a hypothetical “historical, consequential”: “What would the world have looked like now, if we had removed car-driving?” Such historical consequential questions can be answered by applying the same consequential methodology as for prospective questions, but using current or historical data. As pointed out by Guinée et al. (2001, part 3, p. 14), outside such a consequential context, there is no objective way to separate the system of car driving from the rest of the technosphere (i.e. to draw the dotted line in the left circle in figure 1.3), since all product systems are ultimately linked (i.e. there are so many lines crossing the dotted line in the left circle in figure 1.3 that the drawing of this line will imply a number of normative cut-offs). Thus, outside of a consequential context, any separation of product systems will be inherently normative and will therefore have to be included in the question asked, i.e.: “Providing we use method X for dividing car driving from the rest of the technosphere, what is its environmental contribution?” implying that the question carries the premises for its own answer. Such questions, and the LCAs that are used to answer them, may therefore more correctly be termed attributional (Heijungs 1997, Frischknecht 1998, Hofstetter 1998) than retrospective, since they deal rather with the juridical issue of allocation or ***attribution*** of guilt, blame or responsibility, than with the natural science issue of analysing causalities and ***consequences***, and since such questions of guilt, blame or responsibility may pertain to the future as well as the past. The term retrospective, if used at all, should then rather be used for the “historical consequential” applications (see also figure 1.4). The point made here is not that attributional ***questions*** are meaningless, but that it is impossible to give meaningful, ***objective*** answers to such questions. In terms of uncertainty, this may be considerable in consequential LCA, since current uncertain knowledge is used to assess future consequences. However, this uncertainty can be estimated and controlled, while the error that is inherent in attributional LCA is fundamentally unknowable and uncontrollable.

Figure 1.4. Relationship between the distinctions retrospective/prospective and attributional/consequential.

	Attributional	Consequential
Retrospective	Allocation of responsibility to past actions (Who shall we blame for the way things are?)	Causal explanation of consequences of past actions (What would have happened if we had or had not done this?)
Prospective	Allocation of responsibility for future actions (Who shall we blame for the way things will become?)	Causal explanation of likely consequences of future actions (What will happen if we do or don't do this?)

In the past, life cycle assessments have primarily been applied to consequential questions, and practitioners have sought to adjust their methodologies to reflect this objective. However, attributional methodologies have often been applied, because adequate consequential methodologies have been missing. We hope that the market-based methods presented in this report will help practitioners to apply a consequential approach more consistently throughout their life cycle studies.

The relevance of attributional LCAs have been defended with a number of different arguments, which will be treated separately here:

- Attributional LCA may be used as a pedagogical introduction to a life cycle study, since at first sight it may appear simpler: All that is needed is knowledge on current or potential suppliers and customers – other market relations may be disregarded, and data need only be collected from enterprises in one's own supply chain. This may be useful in the early stages of a life cycle study, where there is a need simply to explore the life cycle, to increase the understanding of the product chain (Tillman 2000). An attributional LCA may pinpoint the processes and relations most important to influence in a product system (known as "hot-spot-identification"). However, this could equally well (and maybe even more sensibly) be done with a consequential LCA that tells about the consequences of producing, using, and disposing a quantity more or less of the investigated product. And this would even provide more relevant information on what parameters guide the behaviour of the investigated product systems.
- To operate an LCA-based system for environmental product declarations, there must be a generally accepted set of rules for how to perform such LCAs. Tillman (2000) doubts whether it will be possible to establish the necessary consensus within a consequential approach to LCA since this implies system expansion (see chapter 5) and use of marginal data (see chapter 4), including "an approach as to which marginals and in which way the system should be expanded." The present report, and the two guidelines that it supports, is nevertheless a report on an attempt at providing such consensus. And in response to Tillman's doubt, it appears equally questionable (if not more so) that the necessary consensus and acceptance can be obtained for an attributional approach to LCA that needs to apply and justify arbitrary allocations and choices of which averages to use.
- Additivity between individual parts of a life cycle (enabling a producer to add his own environmental exchanges to those reported by his suppliers)

and completeness (in the sense that only negligible parts of the product system are omitted) are both features that Tillman (2000) use as arguments for using attributional LCA. However, in the sense described here by Tillman, both additivity and completeness are also features of consequential LCA as described in this report.

- Attributional LCA are also said to be applicable in situations where no specific change is planned, as may be the case e.g. for hot-spot-identification, for setting priorities that do not immediately involve a change, or where the scale or products involved in a substitution are unknown, while it is questioned (also by Tillman 2000) how this could be done in a consequential LCA. However, a consequential LCA may very well assess the consequences of production, use and disposal of a defined quantity more or less of the investigated product. This can be done independently for any product, without prior knowledge on the specific comparison that each assessment may later be used for. Later, when specific comparisons are required, these may be obtained simply by subtracting the individual product systems. These comparisons will be valid as long as the product quantities studied are small. For larger quantities it is of course important to include any influence on the boundary conditions.
- System expansion as an important method in consequential LCA to handle systems with multiple products (see chapter 5) is thought by Tillman (2000) to imply “a larger system and thus more data to collect.” Since most LCA databases are currently based on average data without concern for market mechanisms, an LCA based on available data and default cut-off criteria will of course be easier and less time consuming to perform than a consequential LCA that must rely on not readily available market data. However, in an LCA that involves specific data collection, the procedures for consequential LCA suggested in chapters 4 and 5 specifically ***reduces*** the size of the system to investigate by excluding all processes that do not change as a consequence of the change in demand for the product under study. In contrast, a product system in attributional LCA must include, for every step (tier) of the life cycle, all specific suppliers to the previous tier (and even more individual suppliers when average data are used). Our experience shows that for more detailed LCAs that place a large demand on specific, high-quality data, the additional time spent in collecting market data (see section 2.5) will quickly be outweighed by the timesaving in having fewer processes from which to collect detailed environmental data.
- In an assessment of policy options, the decision-maker may be interested in how to change or influence the markets, and is therefore not interested in limiting the analysis to the predicted market reactions to the potential decision, as implied by a study of actual consequences. In LCAs performed for a decision-maker with a long time horizon and a strong influence on the actors and markets in the product chain (such as studies by a market-leader or studies aimed at societal action plans and legislation), the flexibility of attributional LCA to include any process of interest, may better reflect the actual flexibility of the decision maker. However, even in such cases, where the normal market mechanisms are overruled, the market-based procedures of consequential LCA (see the following chapters) will still provide a good framework for explicitly documenting this dominating influence of the decision-maker.
- Because consequential LCAs only look at the consequences of changes, it may misrepresent the “signal value” implied in a demand for an environmentally improved product if this demand does not lead to an

immediate change. An example of this may be the initial immature market for ecological foods, where an increase in demand may not lead to an increase in production, because of the transaction costs of the initial small quantities or because of the time it takes to implement the new technology on the farms. An LCA should give credit to such a demand even if it does not lead to changes in production in the short term, because the combined demand of many actors would be able to overcome the outlined constraints. An attributional LCA can give such a credit, since the attribution is not dependent on any assessment of actual changes. The answer of consequential LCA is to expand the scale and time horizon for assessing the consequences so that the long-term reaction of the market to the change in demand is indeed included, and the credit therefore assigned (see section 4.3).

- Attributional LCA may be used in a context where the decision-maker wishes to support, be part of, or otherwise be associated with what is deemed to be a "good" system, or to be dissociated with what is deemed to be a "bad" system (Ekvall 1999, 2000, Ekvall et al. 2001a, b). For example, the decision-maker may wish to be associated with companies that use renewable energy sources, disregarding whether this leads to increased production of renewable energy or not. A consequential LCA would not be able to provide the sought-after information, since it only takes into account the actual consequences and therefore only gives a credit for renewable energy when an increase in the capacity of renewable energy can be expected (see section 4.3). If no change is expected in the composition of the overall output, for example when the renewable energy source is constrained, as is the case with hydropower in Europe, the consequential LCA does not give any credit (see, however, the exception dealt with in the previous bullet). In this situation, an attributional LCA may well give a credit for a supply of hydropower, simply because it is the association with the "good" system that is credited, and not whether there is any overall change in environmental impact. It should be noted that in the opposite example, where the decision maker wishes to dissociate from what is deemed a "bad" system, e.g. one associated with hazardous chemicals or ionising radiation, the consequential and the attributional LCA would both be able to supply the desired information, since it is very few systems that are downwards constrained, which implies that an explicit reduction in demand would indeed have consequences for these "bad" systems. Ekvall (2000, Ekvall et al. 2001b) seek to justify attributional LCA by referring to rule ethics (as opposed to utilitarian or situation ethics which would support consequential LCA) but acknowledges that its application would require an agreement on what is regarded as "being associated with." This agreement would amount to a rule for allocating or attributing guilt, blame or responsibility, which cannot be made on objective grounds, as noted above. Furthermore, the concept of "being associated with" is hardly meaningful beyond a few steps backwards or forwards in the supply chain, thus rendering LCA too sophisticated a technique for identifying the relevant associations. Nevertheless, it is natural that a commissioner of a life cycle study may feel that it is more relevant to study the processes in the immediate supply chain than those actually affected by the product substitutions. It is important to clarify whether the interest of the commissioner is really in the environmental impacts of products (i.e. in LCA) or more in the environmental impacts of the supply chain as such, since the latter interest may be better handled through supply chain management.

- Ekvall et al. (2001a, b) provide a specific thought experiment where consequential LCAs would lead to an undesirable effect: The lack of credit for using hydropower may provide an incentive to create a separated, sub-optimised market for hydropower where this credit could be justified. However, the thought experiment depends on two conditions being simultaneously fulfilled, namely that the environmentally preferable process or technology is more competitive (cheaper) than the environmentally less preferable, ***and*** absolutely upwards constrained in its ability to change its capacity as a result of a change in demand. In practice, we have not been able to identify any other examples than hydropower, where these conditions occur simultaneously. Nevertheless, this is a real and undesirable effect of consequential LCA, which cannot be avoided but only alleviated or internalised by applying in this situation an additional scenario in which the separated, sub-optimised market is assumed realised, implying thus a credit to the users of the environmentally preferable technology. When so applied, this scenario would work counter to its own fulfilment and counter to the described undesired effect. This isolated undesirable effect of consequential LCA does not in itself constitute an argument for a more general use of attributional LCA.

If a company or product chain in an expanding market has several production lines, some older more polluting and some new less polluting, it may appear with a below average environmental performance in an attributional LCA that use average data, while a consequential LCA that focus only on the new production lines that will be installed, may show a performance equal to the rest of the market, since all actors on the market typically install the same new technology. It may be argued that an attributional LCA will provide an incentive for improvement of the older, more polluting production lines, in order to better compare with “green” competitors that have only newly installed production lines, while the consequential LCA does not provide the same incentive. The attributional LCA can be said to reward the newcomer that is not burdened with the old technology, while the older factory is punished for having been in business longer. However, there is a way for the older factory to avoid this, namely by separating the old and the new parts of the factory, selling the products from the old production lines to the general customer, and selling the now competitive products from the new production lines on the “green” market. This restructuring would not change the overall environmental impact and the attributional LCA would not have provided any more incentive for improvement than the consequential LCA. In contrast, consequential LCA ***does*** provide a real possibility to reward improvements in older production lines even when these are not immediately affected by changes in demand. This is possible if the producer actively links his improvements in the older production lines to increases in sales. Thereby, the customer buys both a product from the new production line and a share of the improvements of the older production lines, which obviously provides a better environmental performance than just buying a product from the new production line. In fact, such cross-subsidising between production lines need not be limited to the production lines within the same company or product chain, if the money is better spent on environmental investments elsewhere. However, to be credible, such cross-subsidies should binding and verifiable (e.g. contractual) and their existence preferably verified by an independent third party. In this way, consequential LCA allows any production to obtain an environmental “credit” when consciously affecting a specific production, while those who only do what everybody else do, obtain the same LCA result as everybody else, no matter how good or bad their average performance.

The understanding of consequential life cycle assessment as a tool for decision-support as opposed to a tool for documentation and attribution of guilt, blame or responsibility, implies a focus on the importance of system boundaries and market data. This implies also a focus on the problems involved in verifying such information, including the involvement of stakeholders, critical assessment of sources, and peer review. This is common to other decision-support tools, which are also not expected to result in unambiguous information, but rather different scenarios where the different assumptions are documented.

1.3 Product substitution

In a consequential, comparative life cycle assessment, the object of study is the environmental impacts of a potential product substitution, i.e. the replacement of one product or group of products with another product or group of products, fulfilling the same needs of the customer. We define a product also in terms of its production process, which implies that a product substitution will always imply one or more process substitutions (understood as process changes or complete replacements), and that a process substitution can also be seen as a product substitution, even when the product itself is unchanged (e.g. in terms of its physical properties).

Product substitutions may occur anywhere in the life cycle, from raw material substitutions, over substitutions in the production and use stages, to substitutions between alternative waste handling options.

In this context, several authors (Clift et al. 1998, Frischknecht 1998, Tillman et al. 1998) have suggested that a distinction between foreground and background processes can be useful. However, we have found it necessary to define these terms more strictly[9], to understand that:
- a foreground process is a process whose production volume will be affected directly by the studied change,
- a background process is a process whose production volumes will not be affected or only be indirectly affected (i.e. only through the market) as a consequence of the increase or decrease in demand as a result of the studied change.

Life cycle assessments are typically limited to study the effects of substitutions at one specific stage in the life cycle, the range of possible substitutions at that stage being delimited by the functional unit (i.e. the functional unit typically does ***not*** specify what choices to make at other stages). The reason for this is that life cycle assessments are typically aimed at situations where the influence of the decision-maker is limited to the specific substitution studied. (i.e. most processes are in the background).

However, if the decision-maker is able to affect substitutions at different stages in the life cycle (i.e. using foreground processes for these), these

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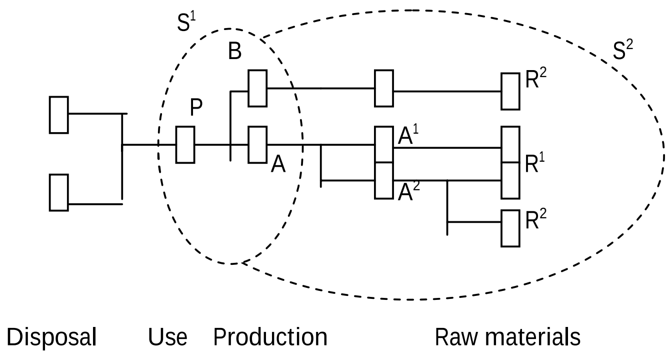
[9] It is worth noticing that in the following methodological explanations, we have *not* relied on these terms but only used them in brackets to show the places where these terms *can* be used. Our point in doing this is to show that, even with our more precise definition, the terms are not necessary, and since they are often used without a precise definition, they may be more misleading than guiding. We therefore suggest that these terms should not be used in general for systems descriptions.

substitutions may - both in principle and in practice - be specified by the functional unit, thus including simultaneously all possible choices in the study.

Even when the decision-maker is not able to directly influence any substitutions elsewhere in the life cycle (i.e. when most processes are in the background), the studied substitution at one stage in a life cycle (the foreground) may still lead indirectly to product substitutions in other life cycle stages (in the background), due to the change in demand implied by the initial substitution. These substitutions are then not included in the functional unit, but the ***expected result*** of the substitutions (in terms of affected processes and their technologies) is simply included when modelling the product systems.

Put very briefly, using the terminology of foreground and background processes: Product substitutions in foreground processes may be included in the definition of the functional unit, while substitutions in background processes are simply accounted for by including the affected processes and technologies when modelling the product systems. See also figure 1.5 and the explanatory text to this figure.



Explanations to figure 1.5: The substitution studied may be at the use stage (to use product A or Product B for the function P), at the production stage (to produce product A by route A^1 or A^2), at the raw material stage (to use raw material R^1 or R^2) or at the disposal stage. However, the choice of a specific product (say B) will typically imply a choice of production route and raw materials (R^2) that is not put into question. It is only when the decision maker (in the case of the choice A or B, the user is the decision maker) has an influence on the choice of production and/or disposal route and/or raw materials use, that the other choices (e.g. A^1 or A^2 and R^1 or R^2) can be included by the definition of the functional unit (e.g. specifying: "P produced using raw material R^2", or the more conditional specification: "P produced with optimal raw material choice," which allows a comparative investigation of different raw materials). This is illustrated by the sphere of influence S^2. Usually, the influence of the decision-maker is more limited, typically to the choice between different products at the previous stage in the product chain (S^1). In this case, the functional unit is simply specified as "P" without indication of any specific conditions of production or disposal. Nevertheless, these choices will still be made by other decision-makers in the chain. So what will be included in the life cycle study is the expected result of these choices, i.e. the expected route of production and disposal as chosen by the decision-makers for these stages of the life cycle.

Figure 1.5. Product substitutions in relation to the sphere of influence of the decision-maker

Relating this to the application areas in figure 1.1, it can be seen that the conditions for a large area of influence (S^1 in figure 1.5) is limited to the upper left-hand corner of figure 1.1, as can also be seen in figure 1.2, namely for long-term, strategic applications involving relatively well-defined products from enterprises with a relatively large (expected) influence on the different actors in the life cycle.

For a thorough understanding of a specific product substitution, information is required on:

1. The extent of the studied substitution, where:

- small[10], short-term substitutions affect only capacity utilisation, but not capacity itself,

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[10] In earlier presentations of the procedure to identify the processes or technologies affected by a substitution (e.g. Weidema et al. 1999), the term “marginal” was used extensively to signify small changes and the processes they affect. In this report, as well as in the guidelines, we now generally avoid

- small, long-term substitutions affect also capital investment (installation of new machinery or phasing out of old machinery),
- large substitutions affect also the determining parameters for the overall technology development, i.e. the constraints on the possible technologies, the overall trends in the market volume, or the production costs of the involved technologies, so that the studied substitution in itself may bring new technologies into focus.

1. 2. The market segment affected, as determined by the obligatory product properties (i.e. properties that a product “must have” for a customer in that segment to accept the products as comparable and thus substitutable).
2. Product availability, i.e. whether the market situation actually allows a choice between the products to be made (markets and/or production technologies may be constrained by market failures, declining markets, regulations, or shortages in supply of raw materials or other necessary production factors).
3. The positioning properties of the products ("nice to have"), as well as price and information, which influences the degree to which a potential product substitution will actually be realised.

This is further elaborated in chapter 2 of this report.

1.4 Defining the functional unit

The functional unit plays several roles in a life cycle study:

- First, it serves as a reference unit, to which all other data in the study relates.
- Secondly, it reflects the amount of substitutions that the decision maker desires to influence, as outlined in section 1.3 (see especially figure 1.5),
- Thirdly, it is the basis of equivalence, when comparing different product alternatives in consequential studies.

For the latter role, the obligatory product properties must always be taken into account. To obtain a precise and unambiguous definition, it has proven useful to analyse in detail the actual obligatory product properties required by the relevant geographical markets and market segments.

A company-internal study comparing different options in the product development, may define additional properties as obligatory for their own brand, although they are only regarded as positioning properties on the general market (and would be determined as such in a more generic life cycle assessment comparing this brand with other brands).

Whether the other aspects of product substitution (availability, positioning product properties, price, and information) should also be taken into account depends on the time horizon of the study. In studies with a long time horizon (e.g. product development or strategic management), it may be reasonable to compare two products, for which substitution cannot be immediately realised,

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the term, as it is in everyday-language used in many different meanings and may therefore give rise to confusion. We suggest to use it only to distinguish between small (marginal) substitutions, where an increase and a decrease will affect the same process, and large substitutions where this may not be the case.

but where it is assumed that substitution will be realised under specific, future conditions of availability, price and product information. The shorter the time horizon of the study, the less relevant it is to include product alternatives, for which substitution is not likely to be realised under the present market conditions.

Two products may be compared even when they differ with respect to positioning properties. If these positioning properties can be determined to fulfil specific functions, equivalence between the products under comparison must be ensured by treating these functions as co-products (see section 1.7 and chapter 6).

1.5 Market-based system delimitation[11]

As mentioned above, the processes to include in a consequential life cycle study - and the technologies of these processes - are the processes and technologies actually affected by the studied product substitution (as defined by the functional unit). To identify the processes affected, all four types of information on product substitution mentioned in section 1.3 are relevant. In chapter 4, we present a step-wise procedure for identifying the affected processes through a formalised treatment of the last three types of information.

Figure 1.6 can be used to illustrate the difference between such a consequential, market-based system delimitation, and the more traditional system description based on an attributional or accountancy approach, where material and energy flows are followed mechanically from process to process. In the figure, it is shown how a change in volume of one process (process 1 to the right) leads to a change in the demand for one of the raw materials to this process. However, many different technologies or processes can meet the specifications for this raw material supply. This is illustrated by the fully drawn processes to the left, which together make up the suppliers to the market. Now, the traditional system delimitation will either include an average of all these processes, weighted by their respective production volumes, or just include that specific process, which represents the current supplier to process 1, here illustrated by the fat box.

When applying an average, the result can be seriously affected by the delimitation of the market on which the average is taken. For example, it will make a large difference whether you regard the Nordic electricity market as one (relatively closed) market, so that Danish electricity consumption is calculated as an average of Danish, Finnish, Swedish and Norwegian electricity production, or whether it is assumed that Denmark is a market in itself (which is often seen in life cycle assessments). If we choose to look at the average for Denmark, which is ***not*** a closed market, it is decisive whether the average is calculated from the Danish production alone or whether you take into account the exchanges with the neighbouring markets, and ***how*** you take this into account, e.g. whether you calculate with Danish production plus import-mix (in periods with much available hydropower in Norway and Sweden), with Danish production plus import-mix minus export-mix (in periods with little hydropower available) or just Danish production plus net import/export (thus disregarding transit-trade). For Switzerland, having a large degree of transit-trade, Ménard et al. (1998) have shown how such

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[11] An early version of this section was published in Guinée (1999, pp. 33-46).

different assumptions affect the average from 21 g CO_2 (Switzerland's own production) over 140 g CO_2 (Switzerland plus import minus export) to 500 g CO_2 (UCPTE average, in that UCPTE can be regarded as a relatively isolated electricity market like the Nordic). The recommendation of Ménard et al. (1998) is to use the model that disregards transit-trade (48 g CO_2) with the argument that this best reflects the actual market conditions. It should be clear from this example that averages can be highly debatable, and possible arguments for preferring one average over the other is actually often market-based. This may in itself be regarded as a serious argument for taking the full consequence, and use a truly market-based system delimitation instead of the average approach.

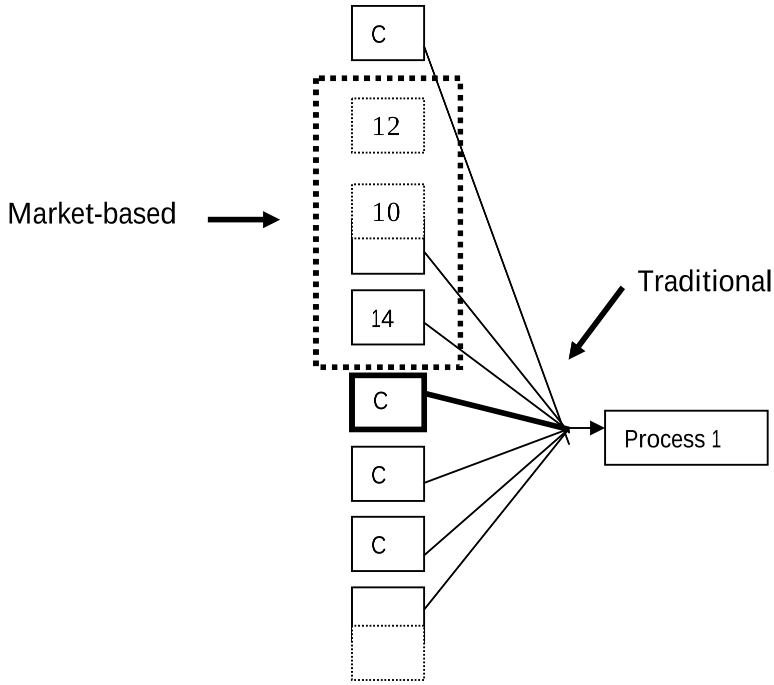


Figure 1.6. Theoretical illustration of the difference between market-based and traditional system delimitation in LCA

A market-based system delimitation will first determine the actual geographical and temporal market boundaries (see section 2.1), which in the electricity example will lead to the identification of the Nordic and the UCPTE markets as being the relevant electricity markets.

Within each such market, a market-based system delimitation will then - instead of considering averages - investigate whether any of the processes delivering to the market are constrained in their capacity to change as a result of a change in demand from process 1 (figure 1.6). These constrained processes are marked with C's.

It should be noted, that also in a market-based system delimitation, the directly delivering process (the fat box) may well come into play. However, this requires that the change in demand overcome the constraints on the process, so that its production volume is actually affected. Thus, the change in demand must to some extent put the market forces out of play to ensure that a capacity adjustment is actually taking place in that specific process. This may especially be the case if the customer has a controlling influence on the supplier (possibly in the form of a monopoly position).

Another aspect of the market-based delimitation is that it investigates whether the change is so large that it gives room for new technologies (illustrated by the perforated box in the upper end of figure 1.6) or that it can affect one or more of the identified constraints, so that a C-marked technology can anyway come into play.

Now, if the technologies/processes in figure 1.6 are arranged in such a way that the most economical are at the top (this is often also the newest and most efficient ones, but this depends also on the cost structure, including the wage level) and the least economical at the bottom (often the older, less efficient), it will typically be either the upper or the lower unconstrained process that will be affected by a change in demand – depending on whether the market is expanding or shrinking. Contrary to the average, we are rather concerned with the extremes here.

If we now focus on the situation with an expanding market, where the possible (non-C-marked) processes are found in the upper part of figure 1.6 inside the perforated box, the final step in the market-based system delimitation is to look at the expected long-term marginal production costs of these technologies/processes (the figures in the boxes). With adequate respect for non-monetarised aspects (flexibility, quality, knowledge), the technology/process with the lowest expected long-term marginal production costs (marked with an arrow) can now be pointed out as the one that will be affected by the change studied.

The outlined procedure is explained in more detail and illustrated with numerous examples in chapter 4.

1.6 Handling co-production

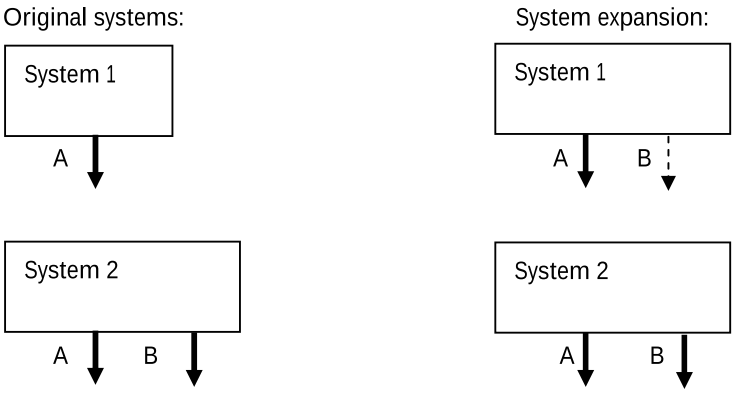
When a process is related to more than one product, how should its exchanges be partitioned and distributed over the multiple products? This has been one of the most controversial issues in the development of the methodology for LCA, as it may significantly influence or even determine the result of the assessments.
The ISO standards on life cycle assessments requires a step-wise procedure to be applied. Besides the obvious solution of subdividing the unit process into separate processes each with only one product, whenever this is possible, the ISO procedure (ISO 14041, clause 6.5.3) consist of three consecutive steps:

- First, when possible, the system should be expanded “to include the additional functions related to the co-products”,
- Secondly, if the above is not possible, “the inputs and outputs of the system should be partitioned between its different products or functions in a way which reflects the underlying physical relationships between them; i.e. they shall reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system”. Clearly, this is a description of causal relationships, implying that the co-products can be independently varied (i.e. a situation of combined production).
- Finally, “where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way which reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products.” Although not stated explicitly, it can be seen from the parallel wording to the second step that the relationships referred to here should also be causal in nature, which is further emphasised by the only example provided, namely that of economic value of the products, which can be seen as the ultimate cause for the existence of the process. Economic value is so far the only causal relationship that has been found to fit this last step of the ISO procedure.

The two first steps of the ISO procedure are only relevant for consequential studies, since they rely on an analysis of relative changes in the output of the co-products and an adjustment of the systems to yield the same output (see also figure 1.6). This means that for attributional life cycle assessments, where such system adjustments are not possible, co-product allocation by economic relationships is the only option left.

In consequential, comparative studies where a co-product does not appear in similar quantity in all systems under study, it is necessary to expand the studied systems, so that they all yield comparable product outputs. The processes to include when making such system expansions must be those processes actually affected by an increase or decrease in output of the by-product from the systems under study (see figure 1.6).

Figure 1.6. Accounting for co-products through system expansion



Explanations for figure 1.6: The two original systems to the left are producing product A either without by-products (system 1) or with the by-product B. System expansion (illustrated in the systems to the left) is performed with the following rationale: If system 2 substitutes system 1, more B will be produced for the same quantity of A. This additional amount of B will substitute another existing production of B, which must then be added to system 1 to take this effect into account. Here, the difficult task is to identify ***which*** existing production of B will be substituted. If system 2 is substituted by system 1, less B will be produced, thus requiring a new substitute production to be added to system 1. Here, the difficult task is to identify ***which*** production of B will be the substitute.

Thus, to identify the processes for a system expansion, one may apply the procedure mentioned in section 1.5 for identifying the processes and technologies actually affected by a product substitution. In chapter 5 it is demonstrated that when applying this formal procedure, system expansion is always possible, i.e. it is always possible to identify those processes that will be affected by a shift between the studied systems. Obviously, the identification can be made with more or less precision, but even an uncertain identification of the affected processes gives a more useful result than an arbitrary allocation according to e.g. economic relationships between the co-products.

From the observation that system expansion is always possible for consequential studies, and never for attributional studies (leaving only the option of economic allocation for such studies), we obtain a much simpler description of the procedure for co-product handling than the description in

ISO 14041, although leading to the same result as when following the ISO procedure.

Also other suggestions for allocation procedures, such as the recycling allocation procedure using material grades (Wenzel 1998, Werner & Richter 2000) and the so-called 50/50 procedure for recycling allocation (Ekvall 1994), can be shown to be simple procedures for system expansion relevant in situations of limited information.

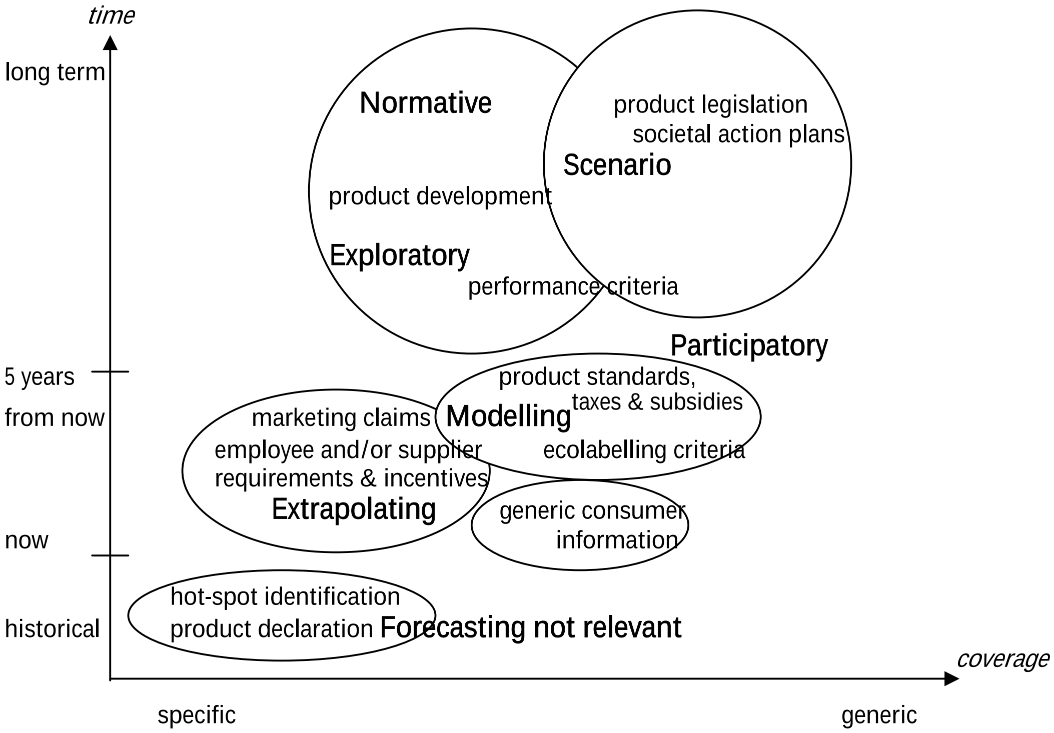
1.7 Forecasting processes

Obviously, forecasting is only relevant for prospective life cycle assessments, where the description of the product systems should reflect the relevant time horizon. It is relevant to forecast:

- the future market conditions determining which future product substitutions will take place,
- the geographical and technological conditions of the future processes, and
- the future environmental exchanges of these processes.

As illustrated in figure 1.7, short and medium term (1-5 years) forecasts for specific product systems may be based on simple extrapolation of trends and historical data. For long-term (5-25 years) forecasts, and forecasts for decisions on less specific systems (e.g. the general disposal system of society), it becomes increasingly relevant to use modelling methods, such as trend impact analysis, which adjusts the extrapolations with the expected impact of mechanisms analogous to those determining past events. For generic studies, aimed at influencing many stakeholders (e.g. ecolabelling), it may be relevant to use participatory methods incorporating the insight and opinions of experts and stakeholders. Scenario methods, incorporating several parallel forecasts, are most relevant for systems used in long-term, strategic studies for both societal decisions and product development. The product development process may also benefit from the systematic creativity in exploratory methods, which combine analytic techniques dividing a broad topic or development into increasingly smaller subtopics or consequences, and imaginative techniques aimed at filling all gaps in the analytical structure. For long-term, strategic applications, involving relatively well-defined products from enterprises where the decision maker is expected to have a large degree of control over the future and the different stakeholders involved, it may be relevant to apply normative forecasting, which investigates how we want the future to be and how to obtain this goal.

Figure 1.7. Relevance of different methods for future forecasting in relation to the application areas of life cycle assessment.



2 Product substitution

We define a product substitution as a replacement of one product or group of products with another product or group of products, fulfilling the same needs of the customer. We define a product also in terms of its production process, which implies that a product substitution will always imply one or more process substitutions (understood as process changes or complete replacements), and that a process substitution can also be seen as a product substitution, even when the product itself is unchanged (e.g. in terms of its physical properties).

Product substitutions may occur anywhere in the life cycle, from raw material substitutions, over substitutions in the production and use stages, to substitutions between alternative waste handling options. In a consequential, comparative life cycle assessment, the object of study is the environmental impacts of a potential product substitution. This product substitution, as delimited by the functional unit, implies a change in demand as the customer replace one product in favour of another: More is bought of the one product, less of the others. This change in demand is transferred all the way backwards through the life cycle stages of the products involved in the substitution (and sometimes also forward, if the substituted products are not completely identical). At the other stages of the life cycle, further substitutions occur, as the suppliers scale their production up or down according to the change in demand.

Thus, product substitution is a core concept to consequential, comparative life cycle assessment. In spite of this, a proper methodology has been lacking for including the available knowledge about product substitution into life cycle assessments. This implies that life cycle assessments have often based their functional unit and system delimitation on intuitive or arbitrary choices, rather than on analytical grounds. This arbitrariness is unnecessary, since knowledge about product substitution is available, although requiring information from sources not traditionally used for life cycle assessments.

The objective of this chapter is to describe the general aspects of product substitution, including the issue of data availability (section 2.5), as well as those procedural steps that are common to the more specific elements of the life cycle assessment method, covered by the procedures presented in the following chapters of this report.

Knowledge on product substitution ***is applied in the following elements of life cycle assessment:***

- When defining the functional unit and which alternative products can be or should be compared (chapter 3),
- When identifying the individual processes to be included in the system under study (chapter 4),
- When identifying the processes to be included in a system expansion to accommodate differences in the functions provided by the compared systems (chapter 5),
- When identifying the processes affected on future markets (chapter 6).

The following sections are structured according to the necessary conditions for a product substitution to take place, namely that:

- the ***products are substitutable***, i.e. that the products have the obligatory properties ("must have" properties) required by the customer in the market segment in question (section 2.1),
- the ***products are available*** to the customer, i.e. that their supply is not constrained by market failures, declining markets, regulations, or shortages in supply of raw materials or other necessary production factors (section 2.2),
- a ***decision is made*** so that the potential product substitution is actually realised (section 2.3 and 2.4).

This division is in accordance with Sheth's theory on buying behaviour that distinguish three main elements in the buying process: product requirements, supplier accessibility and customers ideal and actual choice (Sheth 1973, 1981).

2.1 Product properties and market segments

A product substitution is ultimately a decision of the customer. For a product to be considered relevant for a potential product substitution, the customer must see it as fulfilling the same need. This can be expressed in terms of the ***obligatory properties*** of the product. What is regarded as obligatory product properties change across ***market segments***, and may thus be identified by analysing the requirements on the market in which the product is to be sold. However, in life cycle assessment, it is not uncommon to first describe the product in terms of it properties, and then to identify and describe the market on which it is to be sold. Thus, it is a bit of a "hen and the egg" situation, where the information on obligatory product properties and market segmentation is mutually dependent.

Product properties may be divided in three groups depending on their importance:

- Obligatory properties that the product ***must have*** in order to be at all considered as a relevant alternative. Example: A beverage container must not leak.
- Positioning 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. Example: A beverage container may be more or less easy to handle.
- Market-irrelevant properties that do not play a role for the customer's preferences. Example: A (refillable) beverage container may be more or less easy to clean.

The obligatory properties determine substitutability and are related to market segmentation. Positioning properties may influence the extent to which a potential substitution is actually realised (see section 2.3) and may - together with the market-irrelevant properties - determine the amount of substituted product or the interaction with other product systems. For example, the ease of handling and cleaning a beverage container (positioning and non-market relevant properties, respectively) can influence the amount of car-driving on behalf of the consumer and the type and amount of cleaning agent, respectively.

The same product property may be placed in different groups on different markets (see below).

For a product substitution to be possible, the obligatory properties must be present. Only when these demands are met, the positioning properties can influence the willingness of the customer to switch from one product to another.

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.

Environmental properties may be included among the properties included in the functional unit. However, since the very purpose of a life cycle assessment 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.

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 commercial activities of the supplier.

Markets are typically differentiated

- geographically,
- temporally, and
- in customer segments,

which each have their own uniform set of preferences and demands for product properties.

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.

Temporal segmentation of markets is common for service products (e.g. 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 (e.g. 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***, e.g. 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 positioning properties to become obligatory with time and for markets to become more transparent and geographically homogenous, but at the same time more segmented with regard to quality requirements.

Each geographical market is typically divided into a number of customer segments. Customer segments are generally defined in terms of clearly distinct function-based requirements, i.e. based on the needs fulfilled by the products rather than based 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. 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 (Lancaster & Massingham 1998):
of a size that can provide adequate revenue to support a separate product line.
clearly distinct and 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. For example, the market for office chairs is divided into at least three well distinguished customer segments exit, based on three different working situations: ***The labourer's chair,*** intended for the labourer who is sitting on the chair at intervals only and not for many hours at the time, ***the computer workstation chair,*** intended for the worker who is primarily sitting, and who is working behind a visual display unit at least two hours a day, and ***the manager's chair***, intended for the design-oriented person, not working much on computer or desk, but rather reading, talking on the telephone and the like. The latter chair could typically be for the employer or senior employee, to whom design, aesthetics, and image/representativity to customers are important issues. There is only very little overlap between these groups of customers. The probability that a chair targeted for one segment should sell to a customer in one of the other segments is small, so that the product substitutability from segment to segment can be neglected. This implies that life cycle studies of office chairs should consider each of the market segments separately and not allow for comparisons between them.

2.2 Product availability and constraints in supply

Even when products have the same obligatory properties, they can only take part in a product substitution if they are available to the customer, i.e. that ***supply is not constrained.***

There can be many reasons that a potentially substitutable product is not available to the consumer, notably market failures, declining markets, regulation, and shortages in supply of raw materials or other necessary production factors.

In a market with only one supplier of the specific product (a monopoly), product substitution is per definition not possible. However, few markets are monopolies. 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 substitutions to take place in practise.

In a declining market, the penetration of modern technology is constrained, since new capacity is not being installed, limiting competition to those suppliers already present.

Regulatory constraints typically take the form of minimum or maximum quotas on the process (like the Danish minimum quotas on the use of biofuels for heat and electricity generation) or any of its exchanges, e.g. product quotas (like the EU milk quotas) or emission quotas (like the Danish SO_2 and NO_x quotas for electricity generation, which limits the use of coal based technology). The forced phasing out of specific polluting technologies may also render these unavailable to substitution as a result of changes in demand. Taxes and subsidies may also constitute virtual constraints on production. An example is the negligible import of cereal grains to the EU, because of a very high import tax. Similarly, the farmer's choice of crops is strongly dependent upon the level of subsidies given for different crops, virtually imposing a constraint on crops less subsidised.

The necessary production factors, notably raw materials, 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 products that do not store easily and products and semi-manufactured materials with a low price to weight ratio (such as biomass for energy and paper pulp), 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.

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 studied product has a low value compared to the other co-products, so that the studied co-product cannot in itself provide an economic revenue that is adequate reason for changing the production volume (like animal manure versus milk and meat, or rape seed cakes versus rape seed oil), or if the market trend for the studied co-product is low compared to the market trend for the other co-products. See also section 5.4.

2.3 Realising substitution

Even when products have the same obligatory properties, and an unconstrained supply, substitution is only realised when active ***decisions are made*** by the customer.

In the first part of the life cycle (e.g. in relation to raw material substitution), price tends to play a larger role in purchase decisions and product quality is often less complex, more easy to define precisely, more dominated by technical aspects, and more stable over time than later in the life cycle (consumer products) where complexity increases, preferences change more quickly, and qualitative aspects and irrational behaviour may have larger influence.

It is possible to further subdivide market segments into market niches. A ***market niche*** is a further 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 were only positioning properties in the broader market segment.

Office chair example: Market niches
The substitutability between chairs depends on customer preferences. And these preferences vary from customer to customer. From the 18 years old sporty person, who maybe just wants a chair and gives no thoughts what-so-ever to ergonomic properties, to the older secretary with back troubles. And from the small 10-employee private company to the public institution buying through the public purchase service. Especially within the market segment for computer workstation chairs (see Weidema et al. 2003a), there might be well-distinguished niches between which, the product substitutability is only limited. Examples are:

- ***The niche of occupational therapist prescribed purchase, within which high level ergonomic properties become obligatory, such as synchronic and weight adjusted movements of seat and back rest,***
- ***In Denmark, public institutions of the state, counties, and municipalities can buy through the National Procurement institution (SKI - Statens og Kommunernes Indkøbsservice) that has bulk sales agreements with suppliers. SKI may then in turn specify requirements to be fulfilled by suppliers in order to deliver through SKI, which may include both functional and environmental requirements. For office chairs, these requirements include e.g. ergonomic properties, tests for stability, durability, and strength. Because public purchase is a very large share of the market for office chairs, SKI plays an important role, also in raising the general level of customer requirements.***

Market segments and niches are typically identified by dividing the market according to a number of customer characteristics, such as customer scale, age, sex, education, status, “culture”, attitudes etc. in such a way that demand for product properties is homogenous within segments/niches and heterogeneous between each segment/niche (Lancaster & Massingham 1998). There is also some evidence that market segments and niches may better be modelled by purchase or use context, rather than by customer characteristics, thus allowing the same customer to have different preferences in different situations, and different customers to behave similarly in the same situation (Moss & Edmonds 1997). Edmonds et al. (1997) provide a model algorithm that enables quantitative market segmentation also in situations where domain experts lack confidence in their own judgements or where their initial segmentation is found not to be in accordance with available sales figures. Bech-Larsen & Skytte (1998) provide an example of using conjoint analysis for segmentation of the vegetable oil market into four niches: one with strong preferences for neutral colours and a low content of transfatty acids, one with strong focus on supplier characteristics in terms of quick delivery and ISO certification, one with a strong preference for a high oxidative resistance and antipathy for rape seed oil, and one with strong preferences for neutral taste and a high nutritional value.

2.4 Supply elasticity as a measure of actual substitution

The supply elasticity is a formal measure of the substitution realised (i.e. the change in supply) as a result of a change in an influencing factor, e.g. the demand. If a change in demand leads to a similar change in supply, that supply is said to be fully elastic. If a change in demand does not lead to any change in the supply, that supply is said to be fully inelastic.

On competitive, unconstrained markets (i.e. 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), individual suppliers are price-takers (which means that they cannot influence the market price) and the long-term market prices will be determined by the long-term marginal production costs (which implies that long-term market prices, as opposed to short-term prices, are ***not*** affected by demand). In this situation, the ***long-term*** supply will be fully elastic. In most life cycle inventory models, this is applied as a default assumption: For each process in the life cycle, the demand for 1 unit of product is assumed to lead to the supply of 1 unit of product, and other customers/applications of the product are assumed not to be affected.

Individual suppliers or technologies may be constrained in the long and/or short term and therefore have an inelastic supply. In this situation, the demand will shift to an alternative supplier/technology that is not constrained.

If ***all*** suppliers to a specific market segment are constrained, or if one or more production factors are not fully elastic, a change in demand ***will*** lead to a change in market price and a consequent adjustment in demand (i.e. a behavioural change). This adjustment will be accommodated by the customer(s)/application(s) most sensitive to changes in price, measured in terms of their demand elasticity (i.e. their relative change in demand in response to a change in price).

A special class of constraints are those related to co-production. If the co-producing process is otherwise unconstrained, it is reasonable to apply the default assumption above, that the long-term supply elasticity is fully elastic, also for a determining co-product (see chapter 4 for a definition of determining co-products and a detailed description of our procedure for handling co-products). Thus, the demand for 1 unit of a determining co-product is assumed to lead to the supply of 1 unit of the determining co-product along with the corresponding amount of the dependent co-product(s). Depending on the market situation for each dependent co-product, this additional supply of dependent co-products will go to waste (when the dependent co-product is already only partially utilised), lead to a displacement of the most sensitive alternative supply (when the dependent co-product is already utilised fully and alternative suppliers are not constrained), or lead to an increase in consumption (when the dependent co-product is already utilised fully and all alternative suppliers are constrained). In the situation where displacement occurs, the default assumption implies that the suppliers are price-takers and the co-producing process cannot influence the market price. The market price for the dependent co-product will therefore be determined by the long-term marginal production costs of the displaced supply.

In this way, our treatment of co-production is simply a consistent application of the default assumptions generally applied in life cycle inventory modelling. It therefore appears inconsistent to dismiss our substitution procedure as “fairly unrealistic”, “rather unrealistic”, and to view it “not as part of inventory modeling, but as a type of allocation” (Guinée et al. 2001, part 3, page 125-6, 129). In contrast, Guinée et al. (2001) refrain from modelling the effects of co-production and recommend instead an allocation procedure based on the co-products’ shares of the total revenue. This allocation procedure is equivalent to assuming (see also section 5.10):

- that for any requested co-product a co-producing process will react to a change in demand with an increase in production volume in proportion to the co-product’s share in the total revenue, implying that the remaining part of the demand will be covered by an alternative supply and/or a reduction in consumption elsewhere,
- that the additional supply of other co-products, caused by the increased production volume of the co-producing process, will always be utilized fully and lead to an equivalent increase in consumption (since there is no additional increase in waste handling from the co-producing process, and no displacement of alternative supply) implying that the demand elasticities for these co-products are infinite (even for “near-to-waste” co-products that are partly disposed of as waste),
- that the environmental impacts of the above alternative supply and/or changes in consumption are insignificant (since the system is not expanded to include this alternative supply and/or changed consumption and related processes), and
- that there will be no displacement of alternative supply (i.e. that supply elasticity is 0, even when the supply is not constrained and the same supply elsewhere in the same study may be modelled to respond to a change in demand with the default fully elastic supply).

It is difficult to see how these assumptions can be regarded as more realistic than extending the default assumptions used in the remaining inventory modeling to cover also the situation of co-production.

In fairness, it shall be noted that Guinée et al. (2001), immediately having passed the above controversial and somewhat harsh judgment on our procedure, proceed to recommend the application of our procedure as a sensitivity analysis, “to gain an indication of the possible effects of substitution,” although this may be stretching the concept of sensitivity analysis beyond its original meaning. Rather, the intention is to suggest the inclusion of our procedure as a separate scenario, as an extension “for improving the quality of detailed LCA in these respects where shortcomings are most obvious. A key example is the absence of economic mechanisms in the model, an unfortunate feature in cases where there are extreme inelasticities of supply and demand" (Guinée et al. 2001, part 3, p.59, last bullet). Also in their research recommendations, they suggest: "By incorporating certain economic mechanisms in the inventory model, particularly in cases involving extremely high or low elasticities, inventory modeling might be made more realistic and some of the principal defects of LCA redressed" (op.cit., p. 133). Furthermore, it appears that their judgement of our method has been based on an insufficient understanding: "the … method of Weidema, still difficult to understand, …" (op. cit., p. 128), which is also confirmed by their extensive list of research recommendations (op.cit., p. 133-4).

It should be noted that applying the revenue-based allocation procedure in consequential studies, as recommended by Guinée et al (2001), leads to further inconsistencies when seen in combination with the general recommendation of Guinée et al. (2001) to identify the affected processes in terms of market averages. For example, if we assume that a market is supplied with 10% from a single-product process and 90% from a co-producing process, but this product only contributes with 10% of the revenue, then only a tenth of the co-producing process will be included in the system, implying either an unrealistic decrease in demand elsewhere or that the remaining 90% will be supplied from the single-product process, which is however not consistent with our knowledge that it supplies only 10%.

Further, applying the revenue-based allocation procedure in consequential studies is also inconsistent with defining the functional unit in terms of a single function from a multi-functional process (e.g. the isolated cleaning function of an anti-dandruff-shampoo). When the functional unit comes from a multi-functional process (the hair washing providing joint cleaning and anti-dandruff functions), the demand for the functional unit should – according to the allocation procedure – only affect a part of the analysed product systems equivalent to the share of the functional unit (the price that can be attributed to the isolated cleaning function) out of the total revenue. Nevertheless, when analysing this isolated function, Guinée et al. (2001, part 3, page 78) just mention this allocation procedure as one option, suggesting that the other functions may equally justifiable be either neglected or dealt with through system expansion (adding the anti-dandruff function to the functional unit).

As can be seen from this analysis, all three above elements of life cycle inventory modelling (the method for defining the functional unit, the method for identifying the processes to be included in the system, and the method for dealing with co-production) are interwoven and relate to the same issue, namely that of product substitution as outlined in this chapter. Only when applying the same fundamental method and assumptions for all three elements, as in the following three chapters, a consistent result will be obtained.

2.5 Availability of market data

For the study of product substitutions, and thus for consequential life cycle assessments, the availability of market data is essential. We have therefore investigated the current availability of market data, and have come to the conclusion that availability is a minor problem compared to the availability of technical data on environmental exchanges (the more well-known data availability problem in LCA), although access is still not straightforward.

On the basis of the description of product substitution in the previous sections, five types of market data can be distinguished, the availability of which are discussed separately (illustrated by milk as a specific product) below. Further examples of specific data are provided in chapters 3 and 4.

1. ***Obligatory and positioning product properties in different market segments and geographical markets.*** Information can be obtained from the marketing departments of the enterprises supplying products to the market segment. If such direct information is not available, the same information may be obtained from retailers, industrial organisations, industrial research institutions and industry consultants, regulating authorities and standardisation bodies (issues regulated in national and international legislation and standards will typically be obligatory properties), marketing and consumer research institutions, or trade statistics (the latter especially to document geographical market boundaries). Examples of publicly available information are the analyses of industrial sectors or “resource areas” provided by the Danish Agency for Industry and Trade (Erhvervsfremmestyrelsen 1993a,b,1994a,b, 2001). Weidema et al. (2003a) provide an example of identifying market segmentation and product properties of office chairs, based on a small survey of the Danish market.
   Milk example: Statistical publications have information on market share of various sales channels. Published nutritional surveys of food consumption per population, sex and age group (based on questionnaires) can be used to assess whether and to what extent specific products are consumed in sex- and age groups. Besides such public sources, marketing departments of dairies have a good understanding of the market segments, which they use for planning the marketing their products. The obligatory product properties of milk in each segment: temperature, age after milking, keeping ability, packaging properties etc., are also well known by the marketing departments of the dairies.

2. ***Data on constraints in production and supply.*** Regulatory and political constraints, typically in the form of minimum or maximum quotas, are obviously well known and public (examples: Political decisions not to build any more hydropower or nuclear power plants in Europe, Danish minimum quotas on the use of biofuels for heat and electricity generation, EU milk quotas, Danish SO_2 and NO_x quotas for electricity generation, which limits the use of coal based technology). Constraints in the availability of raw materials, waste treatment capacity, or other production factors are typically well known in the industry and not regarded as confidential. Constraints due to co-production can be determined from their share in the economic revenue combined with their relative market trends, cf. the procedure outlined in section 5.4. In case of missing information on constraints, it should be assumed that there are none. Unjustified exclusion of suppliers is thereby avoided.
   Milk example: Data on milk quotas, subsidies and restitution in the EU are publicly available. The same is true for agricultural fodder crops. Often, it is rather obvious what supplies are constrained, e.g. fodder by-products from the food industry, which depends on the demand for food products, not on changes in demand for fodder.

3. ***Data on market trends.*** This information is typically a combination of statistical data showing the past and current development of the market and different forecasts and scenarios. Trade and production statistics are typically publicly available, either from the national statistics or from product specific industrial organisations. Sector forecasts are typically available from national and supranational authorities, while more product specific forecasts are available from industrial organisations.
   Milk example: Statistical data are published yearly, e.g. sector profiles of the dairy sector with information on spending on milk and milk-products per capita, market share of milk and milk-products and the development in total use of milk and milk-products in kilograms per capita. Sector studies are available in which buying behaviour and scenarios for the future are described. These studies are mostly qualitative.

4. ***Data on the parameters that influence decisions on realised substitution, e.g. prices of different technologies and the effect of information on buying behaviour and investment decisions***. Data on production costs for individual plants, countries, or technologies are obtained from the industry in question, from industry consultants, or from research organisations. Examples are Doms (1993) for data on the U.S. manufacturing energy market, World Steel Dynamics (2000) for data on steel (process-by-process costs and world cost curves replicating key process costs for 284 steel plants in 49 countries), Dernecon (2000) for newsprint, and SRIC (1999) for chemicals. If data cannot be obtained, it may be assumed that modern technology is the most competitive and the oldest applied technology is the least competitive. 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.

   Milk example: Data on the costs of different technologies may be obtained from production engineers and suppliers of machinery. Public sources are not common. Prices of different fodder crops are published and can be used to calculate the changes in fodder composition as a result of changes in production. The most difficult decisions to model are those of the farmers, e.g. how the choice of crops are made. Models can be based on information on the marginal revenue of different crops and the relation between the costs of different inputs (fertiliser, pest control), the influence on the yield, and the price of the agricultural products.

5. ***Data on the scale of change that may influence what technologies and processes to include.*** These data regard boundary conditions of some of the above-described data on market sizes and constraints, market trends, and production costs. Thus, the sources and availability of these data are similar to the above.

A specific problem in data collection for consequential LCAs is that the product substitutions often involve processes that do not belong to the immediate supply chain. This means that data will be required from companies that may not see the immediate relevance of their participation, thus affecting their willingness to supply data. However, practical experience rather suggests that willingness to participate is more a question of the general company culture towards professional secrecy than a question of closeness of business relations.

Just as for technical data on environmental exchanges, market data can be provided in terms of best estimates, best-case, and worst-case data, the latter being suited to provoke data providers to supply data of improved quality.

3 Market-based definition of the functional unit

The functional unit is a central term in LCA, as it signifies the common basis for a product substitution or comparison. In practice, the functional unit is only one specific aspect of the larger task to:

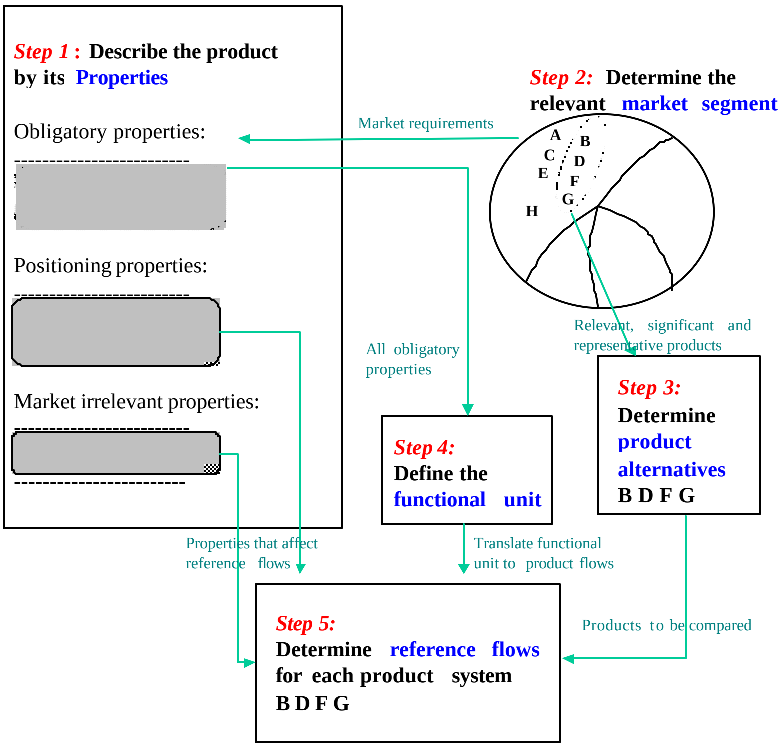
- ***determine the object of study***, thereby making a first delimitation of the product systems to be studied. Example: Artificial outdoor-lighting with daylight-spectrum for existing European fittings.
- ***provide a quantified reference unit*** for all other data in the study (***this*** is the functional unit). Example: Lighting 10 square metres with 3000 lux for 50000 hours with daylight spectrum at 5600 K. The functional unit describes and quantifies those properties of the product, which must be present for the studied substitution to take place. These obligatory properties (the functionality, appearance, stability, durability, ease of maintenance etc.) are in turn determined by the requirements on the market on which the product is to be sold, as already outlined in section 2.1.
- ***determine the reference flows*** that provide equivalence between the alternative product systems in a comparative study. Example: 15 daylight bulbs of 10000 lumen with a lifetime of 10000 hours compared to 6 daylight bulbs of 10000 lumen with a lifetime of 25000 hours. The reference flows translate the abstract functional unit into specific product flows for each of the compared systems, so that product alternatives are compared on an equivalent basis, reflecting the actual consequences of the potential product substitution. The reference flows are the starting points for building the necessary models of the product systems.

For a systematic treatment of these elements of a product life cycle study, we have developed a 5-step procedure:
Step 1: Describe the product by its properties.
Step 2: Determine the relevant market segment.
Step 3: Determine the relevant product alternatives.
Step 4: Define and quantify the functional unit, in terms of the obligatory product properties required by the relevant market segment.
Step 5: Determine the reference flow for each of the product systems.

Table 3.1 gives an overview of the relations between the five steps in the procedure and the above three bullets, which reflect the purposes of the procedure. Figure 3.1 gives a graphical summary of the information flow between the 5 steps.

Table 3.1. The 5 steps of the procedure and their purpose

Steps in procedure	Purpose
1. Product properties 2. Market segment 3. Product alternatives	Determine object of study
4. Functional unit	Provide quantified reference
5. Reference flow	Provide equivalence of product systems



Information flow between the five steps in the procedure

Although the procedure is described in five consecutive steps, it should be noted that it may often be relevant to perform the procedure in an iterative or concurrent way: The product properties described in step 1 may be determined at the same time as, or even from, information on the market segmentation (step 2). The product or the product alternatives (step 3) may be given in advance, and thus contribute to the definition of the relevant product properties (step 1). And the functional unit can be defined (step 4) without having first determined the relevant product or the product alternatives (step 3).

The *two first steps* of the procedure, description of product properties and determination of market segments, are closely related, as already described in section 2.1.

In developing environmentally more preferable products, it is important to understand the relationship between the individual properties and the environmental impact. If the environmental impacts are particularly linked to specific properties, it is especially important to consider whether these ”environmentally costly” properties are obligatory properties that the product “must have” or only positioning properties that it is “nice to have”, and whether it is possible to influence the trade-off made by the customer between the properties in question and the environmental properties of the product, e.g. by environmental information to the customer.

Here, it may also be relevant to consider the concept of market niches (see section 2.3), since the distribution of product properties over the categories obligatory, positioning, and market-irrelevant, may be different for a product aimed at a specific niche than for a product aimed at the general market segment. As an example, an analysis of the US market for manufacturing energy (Doms 1993) show how some operations specifically require gaseous fuels that have the capacity of reaching high, precisely controlled flame temperatures, while other operations have less specific requirements and therefore may substitute between a diversity of sources. In targeting products for different niches, suppliers may utilise such differences in obligatory properties between niches.

Environmentally conscious consumers may give rise to new market niches. This challenge may be met with three strategies for product changes:
a) reducing environmental impact by reducing functionality,
b) reducing environmental impact while maintaining or moderately improving functionality,
c) maintaining or reducing the environmental impact per unit of function while improving functionality.
This is illustrated in figure 3.2.

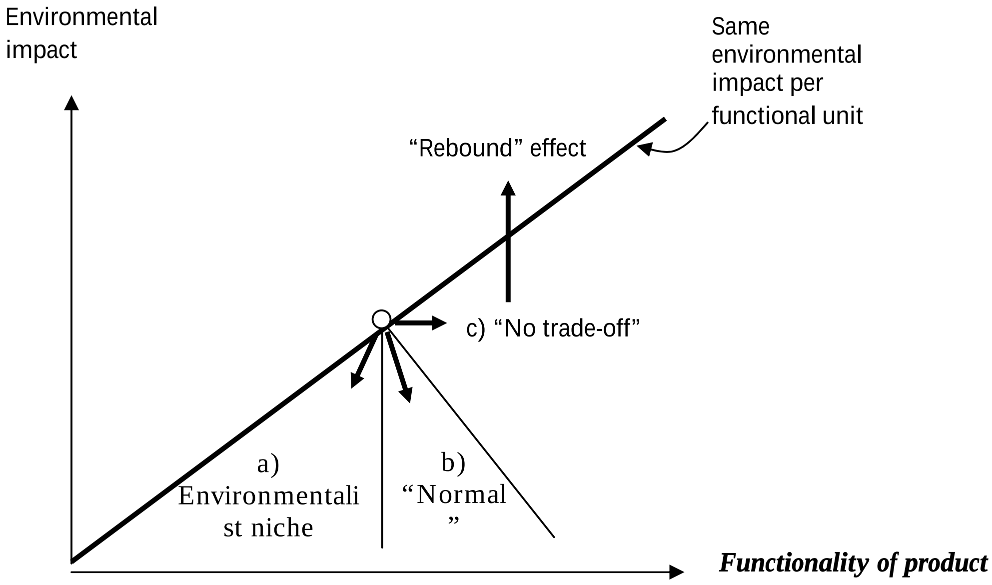


Figure 3.2. Three strategies for reducing environmental impact in respect to functionality, and their market options.

The first strategy will appeal only to a narrow niche of very environmentally concerned customers, with high requirements for environmental properties and low requirements for functional properties. In this niche, the type and number of obligatory properties are reduced compared to the general requirements of the whole market segment. Thus, the functional unit for products aimed at this niche is different from the functional unit for products aimed at the whole market segment. The functionality that is reduced relate to properties that are not obligatory in this niche and therefore not part of the functional unit.

For the "normal" market, reductions in functionality of obligatory properties are not allowed. Here, environmental improvements must be sought that does not compromise functionality. This type of solution may appeal to both the environmentally neutral customer and the environmental conscious customer.

The last strategy, where improvements in functionality are paired with a reduction in environmental impacts ***per functional unit***, may at first sight be seen as an ideal solution implying ***no trade-offs***. However, this strategy may meet some resistance among the more environmentally conscious, since the overall environmental impact may actually increase, if the increase in functionality leads to an increase in the demand for the function, which is a rather common phenomenon also known as ***the rebound effect***. The rebound effect may in fact occur for any type of change, even when the functionality decreases, if the decrease in functionality leads to compensatory actions. Similarly, also the opposite of the rebound effect, a reduction in consumption, may occur as a result of improved functionality ("rather have one piece of high quality than two mediocre"), a parallel to the acceptance of less functionality in the "environmentalist niche." These secondary effects must be taken into account either when defining the functional unit (by using a broader perspective including the behavioural responses, e.g. rather "average work-related personal transport behaviour during one year" than "30000 person-km") or when determining the reference flows (there including the additional processes affected), as further explained below.

The identified market segment or niche may further delimit the products that ***may*** be involved in a product substitution, thus laying the ground for the further specification in ***step 3*** of the product alternatives of what products ***shall*** be included in the study, depending on the goal of the study. For example, an enterprise internal study may be performed for a very specific purpose, which gives a large degree of freedom to define what is regarded as relevant alternatives, while public applications typically aim at influencing a predetermined market and therefore must relate to the products that are (expected to be) available on this market.

What remains in ***step 4*** is mainly the quantification, which should as far as possible relate to the functions of the product rather than to the physical product. For example, rather "seating support for one person working at a computer for one year" than "one computer workstation chair", rather "freezing capacity of 200 dm^3 at -18°C" than "one 200 dm^3 refrigerator", rather "annual lighting of a work area of 10 square metres with 30 lux" than "bulbs providing 30000 lumen for one year". In this way, it is ensured that all obligatory properties - as well as the duration of the product performance - are addressed.

As a reference unit, the size of the functional unit is - in principle - arbitrary. In general, it does not matter whether the office-chair study is normalised to seating support for 0.28 persons, 1 person, 1000 persons or 1.4 million persons. However, two concerns may be relevant when deciding on the size of the functional unit:

- the scale of the studied product substitution,
- the ease of comparison of the outcome of the study to other known quantities.

The studied product substitution may be small or large. A large substitution is defined as one, which affects the determining parameters for the overall technology development. Thereby, the studied substitution may in itself lead to new technologies being brought into focus. It can be a change so large that it affects the general trend in the market volume, e.g. from decreasing to increasing, whereby a new technology comes into play. It may also be a change so large that it overcomes a constraint which otherwise prevents the use of a specific technology. Further, a change may be so large that it affects the production costs of the involved technologies, e.g. through economies of scale. For such instances, it may be misleading if the functional unit is chosen independently of the actual scale of the studied substitution. When studying substitutions involving the entire market of a major product or process, e.g. studies dealing with the entire waste handling system of a region or studies dealing with legislation or standards for an entire sector, it is relevant to choose a functional unit of the same size as the affected market. In evaluating the size of the affected market, it may be relevant to take into account the existence of market niches that react differently to the studied product alternatives, with the aim of quantifying the importance of these niches. While this may affect the chosen ***size*** for the functional unit, it should not affect the ***nature*** of the functional unit (i.e. as defined by the obligatory properties common to the entire market segment studied). Only when studying substitutions in a specific niche, the nature of the functional unit will be affected compared to the functional unit for the entire segment.

Most often, however, life cycle studies deal with small substitutions, which do not affect the overall trends in market volumes, nor the constraints on and production costs of the involved technologies. Therefore, the consequences of the substitution can be assumed linearly related to the size of the substitution so that the precise size of the functional unit will have no importance for the interpretation of the results.

For such small substitutions, another concern may be relevant: When presenting the outcome of the study, it should be as easy as possible to compare the outcome to something well-known to the reader. For this reason, the environmental exchanges are typically normalised to the annual exchanges from a region, from an average person living in this region (person-equivalents as in the EDIP-method), or from the average monetary expenditure in this region. To ease this normalisation, and to present the results in an easily comprehensible way, it may be an advantage to set the size of the functional unit equal or close to the annual per capita consumption of the studied product on the studied market segment.

In some instances, two products may be so closely linked that the separation of some of the processes in their life cycle may lead to an increase in uncertainty. If all the analysed product systems provide the same amount of such linked products, this additional uncertainty may be avoided by including both products in the functional unit.

The final ***fifth step*** in the procedure is to determine the reference flow for each of the product systems. The reference flow is a quantified amount of the product(s), including product parts, necessary for a specific product system to deliver the performance described by the functional unit. For a composite product, the reference flow will typically be identical to the parts list of the product, multiplied by a factor to scale it to the functional unit.

The purpose of the reference flows is to translate the abstract functional unit into specific product flows for each of the compared systems, so that product alternatives are compared on an equivalent basis, reflecting the actual consequences of the potential product substitution.

As noted in section 2.1, it is not just the obligatory product properties that determine the amount of substituted product or the interaction with other product systems. To ensure the equivalence between compared products, it is therefore necessary to analyse systematically ***all*** product properties and judge for each one whether it leads to differences in the amount of substituted product or in the interaction with other product systems. If several such additional properties can be identified, it is important to investigate whether ***one*** of the properties can be identified as the one ***determining*** the difference in performance.

Examples of determining properties[12]:
In comparing different alternatives for hand drying, the technical properties of the tissue paper such as mass, absorption-power and tensile strength, may all influence the number of tissue papers used. However, these properties may all turn out to be irrelevant if in practice it is the dispenser design that determines the amount of paper used. Similarly, technical specifications of electrical hand driers, such as the volume of air and its temperature, may be irrelevant for comparing relative performance, if the actual operating time and energy consumption of the devices are fixed by other factors, e.g. built-in timers that give a fixed time per hand-drying event to be multiplied with the effect of the device (kW/minute).

In comparing alternative types of walls in buildings, the property that determines the material consumption will often vary with the specific type of wall, depending on the chosen material or construction principle. This implies that it is not possible to identify a single determining property common to all the compared wall types. However, for each individual wall alternative, a determining property may be identified. For one wall type, the determining parameter may be durability, for another it may be strength, and for a third it may be sound or heat insulation.

It should be noted that differences in performance between the compared alternatives often appear when choosing a (too) narrow product perspective, i.e. when studying intermediate products, components, or products that are otherwise very dependent on other products. Such performance differences, and the consequent need for adjustments, can often be avoided by choosing a broader function-based perspective, i.e. based on the needs fulfilled by the products (e.g. "lighting" and “cooling of food”) rather than based on the physical products themselves (e.g. "lamps" and “refrigerators”).

Goedkoop et al. (1998) even suggest that 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.”

For each of the properties identified as having a determining influence on the amount of product necessary, a relative measure must be determined of the extent to which the studied products are expected to substitute each other.

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[12] Several of the examples provided in this chapter can also be found in ISO TR 14049, since they were provided as an input to the ISO TC 207/SC5/WG3 by the author.

Examples:
In a comparison of lighting alternatives, 3 bulbs of 3000 lumen may be substituted by 2 bulbs of 4500 lumen if the bulbs can be placed so that the distribution of light is equal (or so that the difference is acceptable to the user). If the bulbs have different lifetimes, the comparison must be further adjusted to take this into account, resulting in reference flows of e.g.

- ***5 times 3 bulbs of 3000 lumen with a lifetime of 10000 hours each, equal to***
- ***10 times 2 bulbs of 4500 lumen with a lifetime of 5000 hours each.***

When comparing paints with the same obligatory product properties (e.g. minimum 98% opacity and minimum 5 years durability), differences in covering ability (a positioning property) will determine the reference flow of the different paints, e.g. a ratio of 2.3 litres of paint A to 1.9 litres of paint B to 1.7 litres of paint C etc.

In comparing different alternatives for hand drying, the dispenser design may determine the size of the reference flow of tissue paper.

In comparing 0.5-litres one-way bottles with 0.4-litres returnable bottles, the amount of bottles needed to fulfil the same function of protecting a certain amount of beverage is determined by two properties: the volume and the return rate of the returnable bottles (with a return rate of 90%, a reference flow of 125 returnable bottles would protect the same amount of beverage as the reference flow of 1000 one-way bottles).

For each of the properties identified as leading to differences in the way that the compared systems interact with other systems, the system boundaries must be modified to avoid this difference. This is parallel to the procedure for handling co-products, which also lead to a need for modifying the system boundaries to include the processes affected by the differences in amounts of co-products from the analysed systems (see chapter 5).

What is important in this step, is the description of the difference between the analysed products and a general description of the system modifications necessary to avoid this difference. The description must include any difference, which leads to additional processes in one or more of the analysed product systems. Also future processes, such as additional needs for maintenance, replacements, waste treatment, or recycling of raw materials must be included in the description, whenever these processes are planned or can be foreseen to be necessary.

Examples:
In the comparison of 3 light bulbs of 3000 lumen to 2 bulbs of 4500 lumen, it may be necessary to include the sockets and other fixtures that may be affected by the choice. Furthermore, if the heat given off from the bulbs (which would normally be a market-irrelevant property) is not equal, this will affect the need for room heating and/or cooling (unless it is an outdoor lighting). Thus, the reduction in heating requirement and/or increase in cooling requirement must be included in the comparison.

In the above example, the difference in lifetime of the two bulbs was simply taken into account when calculating the relative performance of the two light bulbs. While this adjustment may be an acceptable procedure for a comparison of light bulbs, more long-lived products, such as refrigerators with life times of 10 or 20 years it require that technology development is taken into account. One refrigerator with a lifetime of 20 years cannot simply be compared to two successive, present-day refrigerators with a lifetime of 10 years. The refrigerators available 10 years from now are certain to be more energy efficient (i.e. having lower energy input per functional unit) than the present, so the energy efficiency of the second refrigerator of the 10 + 10 years alternative must be determined by forecasting, while the energy efficiency of the 20 years alternative is fixed.

As already noted, the behaviour of the customer may be affected differently by the different product alternatives. This is especially relevant when studying consumer products and may often significantly affect the outcome of the study. Thus, it is necessary to include the entire change in consumer behaviour in the reference flow, if this was not already done in the definition of the functional unit.

Examples:
A comparison of refrigerators may be based on their internal and/or external volume. The primary function is obviously related to their internal volume, but the external volume may be an obligatory property, if the refrigerator is to be fitted into an existing kitchen. If the external volume is required to be equal, the internal volume may differ because of differences in insulation thickness. This may cause differences in behaviour of the user (e.g. shopping more often, storing certain items outside the refrigerator, or adding another secondary refrigerator elsewhere in the house). Each of these changes in behaviour will involve changes in different processes, which then have to be included in the study. If, on the other hand, the internal volume is required to be equal (i.e. is an obligatory property), a change in insulation thickness may require adjustments in the physical surroundings of the refrigerator (the other kitchen furniture). If both the internal and the external volumes are regarded as obligatory properties, obviously no adjustment is possible that can accommodate the change in isolation thickness. This illustrates that the obligatory properties also determine which products it is possible to include in the study.

In the comparison of 0.5-litres one-way bottles with 0.4-litres returnable bottles, it may - as mentioned in section 3.2 - be necessary to investigate how the difference in volume affects the consumption of the beverage. If the consumer regards 1 bottle equal to 1 bottle, the total consumption of beverage will decrease when the returnable bottles are introduced. In this case, the packaging cannot be studied independent of its contents. The goal of the study may then have to be redefined to allow a comparison of beverage plus packaging taking into account the changes in consumption.

If there is a large price difference between different product alternatives at the end consumer level, and you wish to model the environmental impacts of this situation correctly, the reference flow of the cheaper alternatives may have to be adjusted to include the alternative spending of the money saved. This addition should ideally model the marginal spending by utilising information on what products increase their market volume when the spending increases, as presented in figure 3.2.

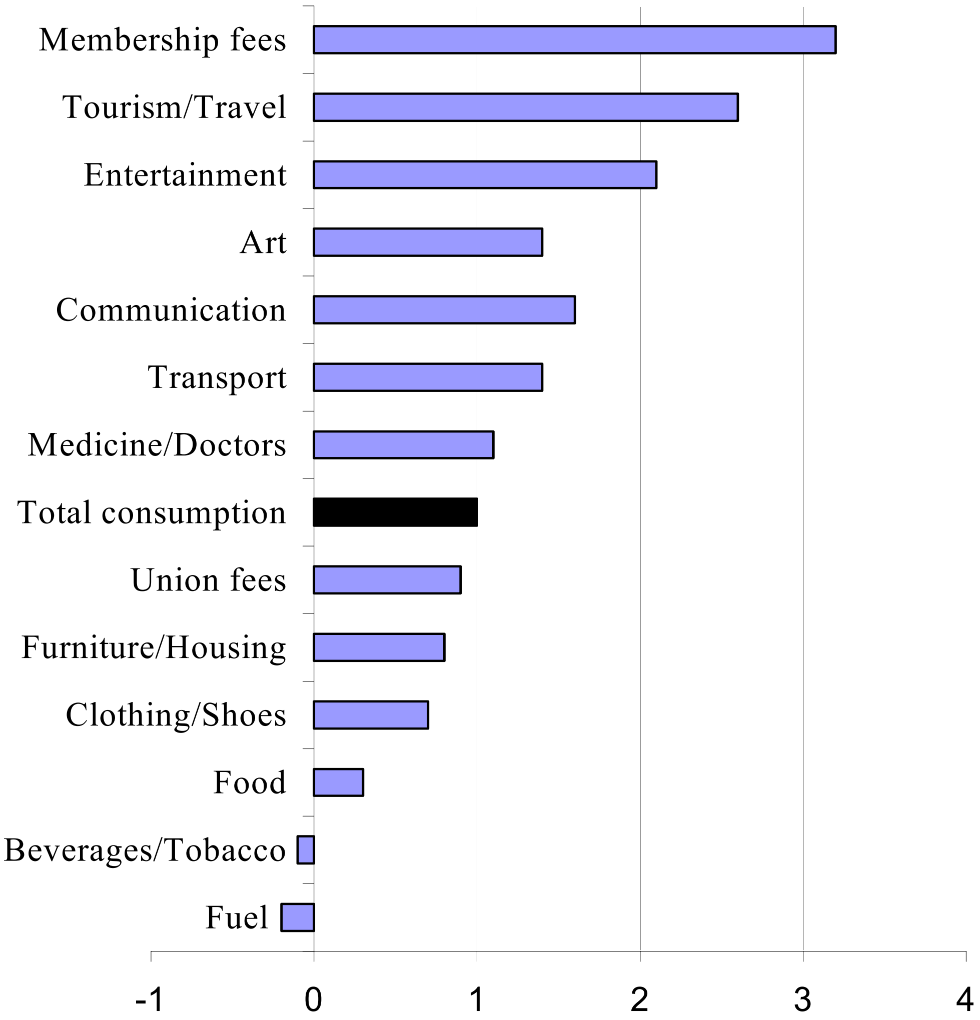

Figure 3.2. The distribution of 1% growth in private consumption in the period 1977-1997 in Denmark. Calculated by the Copenhagen Institute for Futures Studies

Note that this is generally only relevant for price differences at the end consumers, since at enterprises the price differences seldom have any lasting effects due to the tendency of marginal profits and wages to level out across all industries (Hardwick et al. 1990).

A similar adjustment may be required if the there is a large difference between the product alternatives in terms of time consumption at the end consumer level. In this case, the timesaving alternatives may have to be adjusted to include the changes in overall behaviour as a result of the additional time available in these alternatives.

To determine exactly what additional processes are to be included as a result of differences between the analysed systems often requires more detailed investigation. This investigation, which follows the same procedure as for determining the system expansions related to co-products (see chapter 5), does not have to be finalised as part of the procedure described here.

Similarly, the detailed description of the additional processes may be referred to the general description of what is included in and excluded from the analysed systems.

For the final reporting, it is appropriate to report all system expansions in one place, both those relating to product properties and those related to co-products. In order to avoid misunderstandings as to the extent of the systems described by the functional unit, the appropriate place for reporting all system expansions (including those from handling of co-products) is in close conjunction with the description of the functional unit. Also, it is recommended that in the presentation of the outcome of the study (inventory tables etc.), the influences of system expansions should be presented separately.

4 Market-based system delimitation

4.1 Introduction

The idea that market information is important in determining what processes to include in a product system was suggested already by Weidema (1993). Here it was suggested that the actual environmental impacts are most correctly modelled by using environmental data on the marginal technology, defined as the technology actually affected by a small change in demand (Weidema et al. 1999). As mentioned in footnote 10, we now refer to this technology simply as the "technology actually affected," thus avoiding the term "marginal" as it may give rise to confusion due to its many different connotations in everyday-language. Also, compared to the procedure presented in Weidema et al. (1999), the procedure presented here is not only relevant for small (marginal) product substitutions, but has been generalised to cover also larger substitutions.

To build a model of a product system, it is natural to start with the process in which the reference flow occurs (see chapter 3). Each item in the reference flow is then linked to the next process both backwards and forwards in the life cycle. Backwards, the flow typically consists of intermediate products, components, ancillary inputs, and raw materials. Forwards, the flow may also consist of final products, products for reuse or recycling, and waste to treatment. To make it simple, we call all these flows "intermediate product flows". Flows to the environment (environmental exchanges) are typically not included in the first description of a product system.

The purpose of the procedure presented here is to determine the process(es) that a specific intermediate product flow should be linked to, and which therefore should be included in the studied product system. It is for these processes that data on environmental exchanges are later to be collected. The overall uncertainty of a life cycle assessment will often be determined by what processes are included and excluded from the analysed product systems.

A product substitution (e.g. the choice of one chair design instead of another) will result in a ***change in demand*** for the intermediate products that enter into the process in which the substitution occurs (e.g. the steel and plastic components that are used by the chair manufacturer), and likewise in the demand for the further intermediate products backwards in the life cycle (e.g. the plastic raw materials). The procedure presented here identifies the processes that are expected to be affected by such a change in demand for a specific intermediate product.

A product substitution will also result in a change in ***supply*** of the intermediate products ***leaving*** the process in which the substitution occurs, and in supply of the further intermediate products forwards in the life cycle (e.g. the distribution, retail sale, use and disposal of the chair). To make the description less abstract, the explanatory text for the procedure only covers the situation where an intermediate product is followed backwards in the life cycle (identifying the effects of changes in demand). This is the most typical situation, since the functional unit is often determined in relation to the use phase, and most of the life cycle typically comes before this phase. However, the 5 steps of the procedure, the decision tree in figure 4.1, as well as the general concepts in the explanatory text, are also applicable when following an intermediate product flow forwards in the life cycle (identifying the effects of changes in supply). Examples of this are the investigations in section 4.8 of the consequences of a change in supply of dairy products and of waste treatment.

By the procedure presented here, one or more suppliers will be identified as being affected by a change in demand. The identified suppliers will typically use a specific technology and/or be located within a specific geographical region (since differences in market conditions and competitiveness typically depend on geographical and technological differences). The number of suppliers and the degree of detail of describing their technologies, depends on:

- the difference between the suppliers in terms of environmental impacts, since it may not always be necessary to distinguish between individual suppliers, when these use similar equipment and procedures,
- the scale and time horizon of the change, since large scale changes and changes over longer time spans may affect several separately identified suppliers or technologies, while for smaller and more temporary changes one specific supplier or technology may be identified as the one affected.

The implicit assumption of the presented procedure is that one or more suppliers have a fully elastic production and all other suppliers will not be affected by the changes in demand, i.e. having a fully inelastic production. If this assumption is regarded as too simple, the product system should include all suppliers that are expected to change, as well as all buyers that adjust their demand in response to changes in market price. This can be done either as separate scenarios or in the form of an average, weighted in proportion to the relative degree to which the processes are expected to be affected.

The procedure outlined in figure 4.1 consists of 5 steps:
Step 1: Identifying the scale and time horizon of the studied change
Step 2: Market delimitation
Step 3: Identifying the market trend
Step 4: Identifying production constraints
Step 5: Identifying the suppliers/technologies most sensitive to change

In the following sections, we will have a closer look at some of the theoretical issues involved in each procedural step. In section 4.8, we present a larger number of examples where the procedure has been applied in practice.

For the initial phases of a life cycle study, and for parts of the life cycle that are less important, the described procedure may be too elaborate and too demanding. Also, there may be situations where it is not possible to obtain the necessary market information. In these situations, the defaults in table 4.1 may be applied. The arguments for these defaults are given in the following sections.

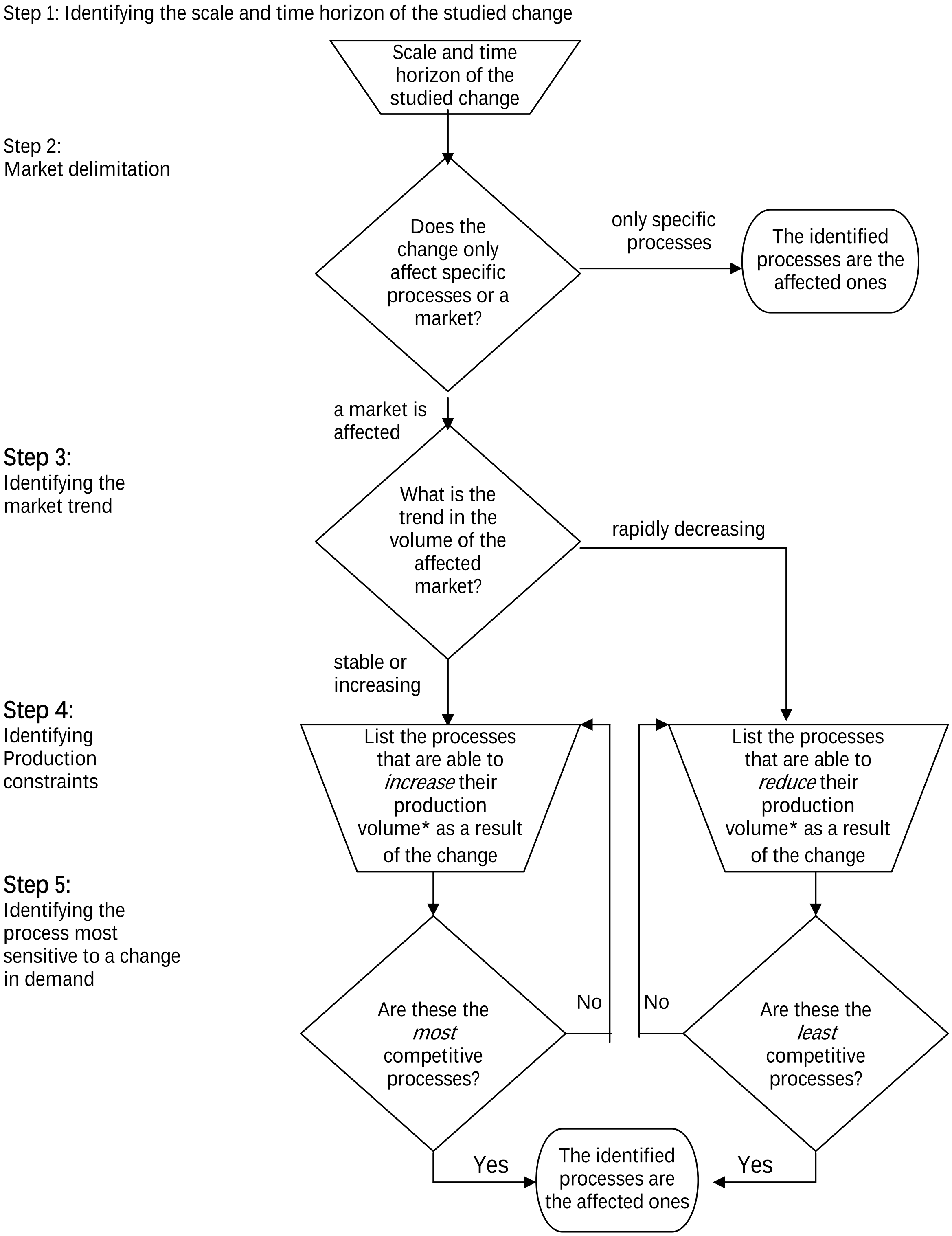

Figure 4.1 Decision tree outlining the 5-step procedure for identifying the processes affected by a change in demand for a specific intermediate product. Please se the text for detailed explanations.

*) For long term changes, the volume relates to production capacity, while for short term changes it relates to output within the existing capacity, see also the text.

Table 4.1. Default assumptions on market conditions (applicable when specific data are not available)

Item:	Default assumption:
Scale of change	Small
Time horizon	Long-term
Market ties	None
Market segment	Narrow, i.e. not assuming substitution between very different products
Geographical market	Products with a low value to weight ratio: Local market Products with medium value to weight ratio: Continental market* Products with a high value to weight ratio: Global market*
Market trend	Overall increasing production volume
Production constraints	Only for co-products with a low value relative to the remaining co-products from the same process
Affected (most competitive) supplier/ technology	Technology: Modern Geographical location (within the above defined geographical market): Depending on relative importance of labour costs and skills.

*Taking into account also possible toll barriers, trade patterns, and geographical differences in overall production volume.

4.2 Scale and time horizon of the studied change

As already pointed out in section 1.3, we distinguish between small (marginal) and large product substitutions (and changes in demand). For small substitutions, we further distinguish between short-term and long-term substitutions.

A product substitution is defined as small or marginal when it does not affect the determining parameters of the overall market situation, i.e. 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 substitution can thus be assumed linearly related to the size of the substitution and both an increase and a decrease in production volume will affect the same processes.

A product substitution is defined as large when it affects the determining parameters for the overall market situation, i.e. the direction of the trend in market volume and the constraints on and production costs of the involved products and technologies. The substitution may therefore in itself bring new suppliers, new markets, or even new products and technologies, into focus. It can therefore not be assumed linearly related to the size of the substitution and increases and decreases in the production volume may affect different processes. For large substitutions, 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, e.g. if all cars were to be made from polymers and carbon-fibres in stead of steel, which among other consequences would 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 a life cycle assessment 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 substitutions studied by life cycle assessment are (unfortunately) not of such significant size. As shown by Mattsson et al. 2001), even a change in electricity demand of 1 TWh can still be regarded as small (marginal), since it affects the same technologies as a change of 1 kWh, the effects thus being linearly related to the size of the substitution.

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

A short-term substitution affects only capacity utilisation, but not capacity itself. A long-term substitution affects also capital investment (installation of new machinery or phasing out of old machinery). Large substitutions will always affect capital investment. But even small substitutions can seldom be isolated to the short-term, 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 (i.e. long term substitutions). This is obvious in markets with a short capital cycle (fast turnover of capital equipment, as e.g. in the electronics and polymer industries) and in free market situations (where market signals play a major role when planning capacity adjustments), but it is also true for markets with a long capital cycle (as e.g. in the building and paper industries). Thus, the isolated effects of short-term changes (i.e. effects within the existing production capacity) are only of interest in markets where no capital investment is planned (e.g. industries in decline), or where the market situation has little influence on capacity adjustments (i.e. 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.

As a default, when specific information is not available, it may be assumed that the studied change is long-term, since this is the typical situation.

If a long-term substitution is planned and announced well in advance of its implementation (as e.g. the installation of a new pipeline), it may involve ***only*** long-term effects, i.e. 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, i.e. 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 new technology (at least in expanding markets), 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 is only lasting until the next capacity change.

Example:
In a factory, several production lines may 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). 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.

4.3 Market delimitation

In most situations, the intermediate product is demanded on a market with several potential suppliers/technologies, which are adequately different to merit a closer investigation as to which ones are actually affected by the change in demand. The ***potential*** suppliers/technologies must be identified in terms of those who (can be expected to) deliver to this market. The market in question is identified by the obligatory product properties and the geographical and temporal market boundaries, i.e. in parallel to the first two steps of the procedure described in chapter 3 (actually described already in section 2.1).

As a default, when no other information is available, narrow market segmentation may be applied, i.e. not assuming substitution among very different products, since this reduces the size of the possible error (assuming a wide market segment implies the inclusion of very different processes, compared to those within a narrower segment).

In the early presentation of this procedure (Weidema et al. 1999), the need for geographical delimitation of the market was not adequately described, which caused some confusion as to the correct delimitation of e.g. the aluminium market. Ekvall et al. (1998) assumed the existence of a European market for aluminium, implying that an additional demand for aluminium in Sweden would lead to an increase in European production capacity. In response to this, Nordheim (1999) pointed out that there is no such thing as regional markets for aluminium, i.e. that aluminium should be regarded as a global commodity, and the affected aluminium production therefore should be determined on a ***global*** market, while the electricity source for this aluminium production will be supplied from several ***regional*** electricity markets, one for each of the aluminium production sites where capacity will be adjusted, see also the elaboration on aluminium in section 4.8.

As a default for geographical segmentation, the value to weight ratio of the products may be applied, being properties that are practically always known and somewhat related to transport distances (see Weidema et al. 2003b), thus being indicative of geographical market boundaries. By assuming a local market for products with a low value to weight ratio, a continental market for products with medium value to weight ratio, and global markets for products with a high value to weight ratio, the possible error is minimised. Gielen (1998b) argue that for most bulk materials, Europe can be regarded as a closed economy. However, when available, knowledge should be applied regarding toll barriers, trade patterns, and geographical differences in overall production volume (such as for products that are only produced in certain locations or where price differences are large between different producing countries), since this can seriously affect the actual market boundaries.

In some situations, the whole procedure may be cut short here, namely when only one supplier is possible, or a group of specified suppliers can be identified as the ones affected. This is the case if:

- the decision-maker for the study is expecting to control or influence the production volume of a specified supplier or group of suppliers, e.g. by contract (see Kåberger & Karlsson 1998), or
- two or more companies are tied so closely together in a supply chain that the production volumes of the specific suppliers fluctuate with the demand of the specific customers.

Many examples can be found of the latter situation, especially:

- When products have a low price compared to their weight, so that transport costs prohibit all other than the local producers, as e.g. 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.
- When two or more companies are tied together by tradition, or when a supplier has developed its product to meet specific demands of the customer.
- When the choice of supplier is not subject to normal market conditions.

If a specific supplier (or group of suppliers) is identified as the one affected, it may be useful to justify that the production volume of this process is actually ***able*** to change. For this purpose, step 4 in the procedure (section 4.5) may be applied.

The procedure can only be terminated here if the production volume of the specific suppliers is actually expected to change as a result of the studied product substitution, i.e. as a result of a change in demand for the intermediate product. If the change in demand is transferred on to other suppliers of the intermediate product, the production volume of the specific supplier will ***not*** change. This may be the case in spite of close relations between supplier and customer, even in spite of ownership relations or sole-supplier-status, i.e. it is not the closeness of the relation, which is important, but whether the overall production volume of the supplier is actually expected to be affected.

An example of this is in-house electricity production. If the in-house production fluctuates with in-house demand and thereby does not affect the production volume of the general electricity market, then the in-house production can be regarded as the affected electricity source for the in-house demand. However, if the in-house production takes place on normal market conditions, and the in-house production does not fluctuate with in-house demand (even when the company is closed), then the electricity supply for the in-house demand must be regarded as coming from the general electricity market, and not from the specific in-house production.

This also means that a consequential, market-based life cycle assessment will only give credit for - and incentive to - a shift to specific products or suppliers with environmentally more preferable technologies, e.g. "green electricity", when this shift is actually expected to lead to an increase in the capacity of the "green" technology. If the shift only pretends to be an improvement, and no change is expected in the composition of the overall output, no credit is given.

However, the effects of a shift may be delayed, so that the expected increase in the “green” technology will only appear after some time. 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, a demand for “green” products should still be credited for its long-term influence on the production capacity of the environmentally preferable technology.

Also, the effects of a shift may be indirect, via the political signal that it sends. For example, a constraint on a specific “green” product may be overcome, e.g. by 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. More speculatively, it can be argued that the credit for a “green” product can be so valuable to the buyer that this alone could lead to a situation in which a constrained market for a “green” product is kept artificially sub-optimised (see Ekvall et al. 2001).

Since such indirect effects may be controversial and difficult to predict, 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, e.g. 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, 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. This is the typical situation, and by this the burden of the proof rests on the companies having established such close market ties, and therefore have the best access to the information on these.

The technology that will be affected at different suppliers may often be the same modern technology, even though they may currently have very different technologies installed (e.g. a company which has been in operation for a long time may be dominated by older production lines, while a factory that has recently entered into the market may on average have a more modern technology). In a consequential, market-based life cycle assessment, both suppliers will appear with the same modern technology, since this is what will be affected by a change in demand. Thus, the company with a longer history will not be punished for its historical investments, nor will the newcomer obtain any advantage from having avoided such a burden of history, as would have been the case if an average, attributional approach had been followed. Instead, the consequential approach will give credit for any supplier that makes an environmental improvement, no matter how good or bad his current situation.

This may raise the concern that such an approach will not give any incentive to the older factory to improve the more polluting parts of its current production equipment, since the factory is anyway judged only on the basis of its new installations. However, the older factory may actively utilise its larger improvement potential by linking investments in new capacity to improvements in its older production lines. Any company may in fact make such linking (cross-subsidising) of two separate productions; it is not necessary that the two production lines be inside the same company, as long as the link is binding and verifiable (e.g. contractual). To be credible, the existence of such links should preferably be verified by an independent third party.

An example of such linking, although with a different objective, namely to ***avoid*** that the premium from the sales of a “green” product cross-subsidises other less environmentally preferable productions, is that of naturemade-Star electricity: This label explicitly requires that the additional income from the premium on the labelled electricity is used to increase the environmentally preferable electricity production from renewable sources and to improve the environmental performance of the existing power plants (http://www.naturemade.org/d/zertifizierung/). Specifically for hydropower, the label requires (according to Frischknecht 2001) that the additional revenue, about 0.03 EUR per kWh, from selling labelled electricity, is used for (percentages from one specific utility, as example only):

- additional distribution and marketing for labelled electricity, directly & through local utilities (31%),
- a promotional model (Fördermodel), implying that per kWh naturemade-star hydro power, 0.025 kWh new naturemade-star renewable electricity (wind, biomass, photovoltaics) must be sold (47%),
- ecological improvements at the power plant (22%).

4.4 Market trends

Within the identified market, not all ***potential*** suppliers/technologies will ***actually*** be affected by a change in demand. For short-term changes (see also section 4.2), the affected suppliers will typically be the least competitive (often using older technology), since it is mostly these suppliers that have capacity available. For long-term changes, the affected suppliers depend on the overall market trend. In a market that decreases (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. If the market is generally increasing (or 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.

Therefore, it is important to identify the market trend (“Is the market increasing or decreasing?”) especially for long-term changes involving capacity adjustments.

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, e.g. 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 specific demand studied. This is because - as long as the overall trend in the market is not affected – it is the same suppliers that will be affected by an increase in demand and a decrease in demand.

Example:
In comparing paper and textile tablecloths, it is the same modern, competitive technology that will be affected in both the paper and the textile product system, even though a shift from paper to textile will lead to a reduction in demand for paper and an increase in demand for textile, and vice versa. This is because the reduction in demand for paper or textile resulting from the shift will not affect the overall market trend for paper and textile, which will still both be increasing. What will be affected is only the size of the increase, i.e. the amount of new technology that will be installed in the two systems.

Market trends are typically obtained by combining statistical data showing the past and current development of the market and different forecasts and scenarios (see also chapter 6). 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, an increasing market may be assumed, since this is – in spite of obvious exceptions - the general situation for most products, due to the general increase in population and wealth.

4.5 Production constraints

As already discussed in section 2.2, a supplier or an entire technology can be constrained in its ability to change its production volume in response to a change in demand, for one or more of the following reasons:

- Market failures, and regulatory or political constraints.
- Constraints in the availability of raw materials, waste treatment capacity, or other production factors.
- If the change in demand is for a co-product, and the production volume of the co-producing process determined by one or more of the other co-products. See section 5.4 for a precise procedure for identifying which co-products determine the production volume of a co-producing process.

See section 2.2 and 4.8 for examples.

The situation of a declining market, see section 4.4, can be regarded as a constraint on modern technology, since new capacity is not being installed, limiting competition to those suppliers already present.

As 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), it should be avoided that a process is excluded from further considerations because of constraints that only apply in the short term (in day-to-day operations, many constraints apply, e.g. in raw material availability and production capacity, that are irrelevant when considering long-term changes).

As a default, in case of missing information on production constraints, we recommend to assume that there are none. Unjustified exclusion of processes is thereby avoided. If a constrained process is thereby included, this will normally be discovered in the next step in the procedure (see section 4.6).

If ***all*** suppliers to a specific market segment are constrained, or if one or more production factors are not fully elastic, a change in demand ***will*** lead to a change in market price and a consequent adjustment in demand (i.e. a behavioural change). This adjustment will be accommodated by the customer(s)/application(s) most sensitive to changes in price, measured in terms of their demand elasticity (i.e. their relative change in demand in response to a change in price). This change must then be followed ***forward*** (downstream) in this lifecycle.

4.6 Suppliers/technologies most sensitive to change

Among the unconstrained suppliers/technologies, some will be more sensitive to a change in demand than others.

As already discussed in section 4.4, the most sensitive supplier/technology depends on the temporal horizon (short-term/long-term) and the current market trend. For long-term changes in an increasing market, the most sensitive supplier/technology is identical to the most competitive, while in a rapidly decreasing market and for short-term changes, the most sensitive supplier/technology is the least competitive.

Competitiveness is typically determined by the production costs per unit. For capacity adjustments it is the expected production costs over long-term that matters. The distinction between constraints (section 4.5) 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 – whether monetarised or not - may enter the decision-making process. When predicting the actual decisions with regard to changes in capacity or capacity utilisation, it is therefore necessary to include all those constraints and non-monetarised costs which are relevant to the decision makers, but on the other hand not such which are not going to influence the actual decisions. The kind of costs included may also vary depending on the interests of the decision makers, e.g. private investors may place less emphasis on environmental externalities than a public investor (Frischknecht 1998).

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, when data cannot be obtained, it may be assumed that modern technology is the most competitive and the oldest applied technology is the least competitive. 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.

4.7 Environmental product declarations[13]

As a specific application of environmental data from the product chain (life cycle data), there is some ambiguity in the way Environmental Product Declarations (EPDs) are viewed by the public and by experts in the field of labelling and declarations. On the one hand, EPDs are seen as declarations of the past environmental impact that the declared product has had up till the point of purchase, and sometimes including the expected use and disposal phases, but not specifically intended to indicate the expected environmental consequences of buying the declared product, in parallel to a declaration of contents, which does not indicate the expected composition of tomorrows product. On the other hand, EPDs are seen as a means for the customer to ***influence*** the environmental impacts of the purchased products, which exactly places a requirement on the EPD that it reflects the expected environmental consequences of buying the declared product compared to not buying it.

These two views on EPDs are not necessarily in conflict, since in some cases the environmental impacts from buying an additional unit of a product may be expected to be identical to the past environmental impacts caused by a unit of the same product. Intuitively, this expectation appears justified, since one would expect that buying an additional unit of the declared product would lead to an equivalent increase in production of this product by its immediate supplier, and in the long term an increase in the production capacity in the current supply chain. In many cases this may in fact be the case, and a declaration based on data from the current supply chain can then be regarded as both useful for the customer and beneficial for the environment.

However, two conditions must be fulfilled for the expectation to be true, namely:
1) that the production capacity in the supply chain is unconstrained (section 4.3), and
2) that the market is not declining (section 4.4).

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[13] This section is adapted from a presentation to the 9th SETAC Europe LCA Case Studies Symposium (Weidema 2001b)

In so far as these two conditions are ***not*** fulfilled, the inclusion of data from the current supply chain into the EPD may be seen as deceptive, as they may mislead the customer as to what are the actual consequences of the purchase. A few examples will illustrate the need for requiring the two conditions to be fulfilled before including data from the current supply chain into EPDs. Also, possible ways of avoiding misleading declarations are discussed in the following.

In Europe, some sources of electricity, notably hydropower and nuclear power, are subject to either physical or political constraints on their capacity. This implies that the production capacity cannot increase as a result of an increase in demand. An EPD based on current data for these sources of electricity will therefore obviously be an attribution of past environmental impacts rather than a reflection of the consequences of an additional demand. Therefore, such an EPD should be issued with an appropriate warning that it should ***not*** be applied in a comparison with EPDs of other sources of electricity in the context of a purchase decision aiming at choosing the electricity source leading to the lowest environmental impact.

In spite of this, there are examples of EPDs of hydropower presented to the public without such warnings, in a way that could lead the customer to think that they reflect the environmental consequences of buying the declared electricity. One such example is the EPD of hydro power electricity from the Lule river (SEMC 1999), which is published without any warnings on the limitations of its applicability, and even on a web-site where you can find statements such as: “Environmentally sound procurement is probably one of the most important applications of EPD´s” and similar statements (http://www.environdec.com/eng/summary/key_issues.asp, latest visited 2001.08.15). Although not explicitly placed as an information for purchase decisions, e.g. in the context of increasing a customers purchase of “green electricity,” it still appears misleading to present the declarations without a specific warning that they should not be used for comparisons with other equivalent products. The Swiss naturemade-star label described at the end of section 4.3 demonstrates that there are other options available.

Besides physical and political constraints as in the above electricity example, constraints may also be found in relation to co-products, and the use of allocation procedures (as opposed to system expansion, see chapter 5) may therefore lead to similar misleading results as the ones shown in the above case. In fact, capacity constraints on specific raw materials or technologies are such a widespread feature in most supply chains, that the two above conditions are seldom fulfilled for all parts of a product chain. This means that in most cases where EPDs are based exclusively on data from the current supply chain, there is a risk that the declarations may be misleading[14].

In Europe, the market for ammonia is declining, mainly due to political constraints on the use of nitrogen fertiliser for environmental reasons (see section 4.8). The variations in environmental impacts of ammonia production may be illustrated by the differences in energy consumption per ton of ammonia between a modern combined plant in Western Europe, at 29 GJ/ton

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[14] While this section deals mainly with environmental product declarations, the arguments and conclusions are equally valid for environmental labelling in general.

(EFMA 2000), and an old plant in Eastern Europe producing at 48 GJ/ton (Patyk & Reinhardt 1997). Considering an EPD on a nitrogen fertiliser produced on the basis of supplies from the modern plant, the inclusion of environmental data from this immediate supplier would not reflect the environmental consequences of buying the declared product. Since the market is declining, no new capacity is being installed, and the purchase of the declared product therefore does not lead to increase in production capacity for this environmentally preferable product, but rather to postponing the decommissioning of an old plant with poor environmental performance. In fact, the declining market may be seen as a special kind of the constraints on increases in production capacity that we encountered in the electricity example. Thus, to bring the declaration in accordance with reality, i.e. to reflect the consequences of the purchase of additional nitrogen fertiliser, the EPD would have to include the environmental data for the old Eastern European plants that would actually be affected by the purchase decision. To avoid this situation, there is another option for the producer of nitrogen fertiliser: To bring the reality in accordance with the declaration. This could be done by creating a separate market for "green" ammonia, i.e. ammonia from modern plants with low energy consumption, etc. If the producer of nitrogen fertiliser placed a requirement on the ammonia supplier(s) to increase the production capacity in proportion to the sale of declared ammonia (somewhat in parallel to the promotional model described above for electricity), the consequences would be that decommissioning of old plants in Eastern Europe would be speeded up, and the declared ammonia would now really be produced on a modern plant, the data for which could then be safely used in the EPD.

In conclusion, there are three ways to avoid the problem of misleading EPDs due to system boundary choices:

1. Issue the declaration with a warning: The EPDs can be issued with a warning that they should not be used for comparisons with other equivalent products. However, this would then not provide any decision support to the customers.
2. Bring the declaration in accordance with reality: The EPDs can be produced under the application of system boundaries that reflect the consequences of the purchase decision, i.e. market-based modelling.
3. Bring reality in accordance with the declaration: The constraints on production capacity can be overcome, e.g. by creating a separate market for the environmentally preferable products, or by a promotional model (as illustrated by naturemade-star), so that the immediate supplier providing the data for the EPD also becomes the supplier affected by the purchase decision.

It should be noted that the background for an EPD based on market-based modelling might be more difficult to communicate to the consumer, since the market-based product system is less intuitively (physically) connected to the product. For example, the overall volume of milk production being constrained by quotas (as is the case in Europe) means that a purchase of 1 litre of milk does not lead to more production of milk, but to less sales of milk for the least profitable application (typically milk powder). Thus, a market-based EPD would not include the agricultural production, since this cannot be changed by the purchase of the declared product. Nevertheless, the consumer may wonder: "This litre of milk I have in my hand must have come out of a cow. Why is the cow not part of the life cycle?" It may be difficult to communicate that buying the milk just means that someone else will not be able to buy it, but that its production remains unchanged. This is further complicated by the fact that the consumer may actually influence the agricultural production even when the overall production volume is constrained, namely by buying ecolabelled (ecological) milk. Such a purchase will (eventually) lead to more production of ecological milk and less production of non-ecolabelled milk for milk powder, which means that a market-based EPD of ecological milk would include the ***difference*** between the ecological and non-ecological agricultural production.

4.8 Examples of the identification of affected processes

We have applied the above procedure to a number of products, to show the different variations and to demonstrate the practicability of the procedure. The procedure has been applied in different degrees of detail, thus also reflecting that the same degree of detail is not always necessary. The degree of detail required in a specific study will depend on the importance of the specific process in that study and the degree of difference between the possible processes.

It can be seen from the examples that the affected suppliers/technologies are often very different from the corresponding average supplying the market. Thus, only in exceptional cases can average data be used as proxy data, when market-based data are not available. This may e.g. be the case when the market in question is supplied exclusively by one main, slowly developing technology. In most other situations, it is preferable to make one or more estimates of the affected process, based on the available data. If you have data for a market average, the market range may be estimated (see Weidema et al. 2003b) and the affected process can then be assumed to be at one of the ends of this range, depending on realistic assumptions with respect to the items listed in table 4.1. When relevant, several alternative scenarios should be included to reflect the limits of knowledge.

The examples provided below are listed in increasing order after their NACE-code. References are provided for each step in the procedure. Unless otherwise stated, the identification is valid for small (marginal), long-term changes in the years 2000-2010. Some examples have been worked out in 1998 and have not been updated since, although more recent data than cited is likely to be available at the time of print. In general, the examples should be used with care, as they are intended primarily to illustrate the principles of the procedure, not as final conclusions or default data.

When applicable, specific data for modern technologies in Europe may be available in the form of reference documents from the European IPPC Bureau (http://eippcb.jrc.es).

Agricultural crops in general (NACE 01.1)

Market ties: -
Market segment: -
Geographical market: EU, due to border tariffs
Market trend: Increase (FAOSTAT)
Production constraints: Limits on fertiliser per ha in some areas. Some crops are regulated by quotas (***Affected supplier/technology***: Current suppliers, adjusting yield per ha by using additional fertiliser. When this is not possible,

or for larger changes, the crop that will be affected in Europe is barley, since this is the crop with the lowest gross margin (Danmarks Statistik 1992, 1997a). This is confirmed by the expectations of the European Commission (1997c) that the crop most affected by changes in the amount of set-aside area is barley. The change in production of barley will then cause adjustments in productivity of other cereals, which can substitute as fodder, notably wheat and maize. The marginal production of wheat will under these assumptions take place in a grain-dominated rotation on mineral soils, since this is where the marginal cost of increasing the yield of winter wheat by the use of increased nitrogen-fertilisation is the lowest (Statens Planteavlsforsøg 1997).

Fodder protein (NACE 01.11)
Market ties: -
Market segment: -
Geographical market: Global
Market trend: Increase
Production constraints: Soy bean import from USA temporarily hampered by disagreements over genetically modified crops. Protein by-products from industry constrained by demand for the main products.
Affected supplier/technology: Soy bean (USA or Brazil). This conclusion is based on calculations (by Mikkel Overvad of DLG fodder wholesalers) using the linear programming tool "Bestmix" applying current prices and constrained supplies of food industry by-products. This can be explained by the fact that soybean is the only protein crop (aside from grains) for which the protein is the main product. Some substitution between grain and protein concentrates is possible, as determined by their relative prices. However, within the next 10 years, the price of soybeans is expected to be well below the price of grain.

Fodder energy (NACE 01.11)
Market ties: -
Market segment: Energy rich part of the diet (basic energy requirement will be covered by roughage).
Geographical market: Global
Market trend: Increase
Production constraints: None.
Affected supplier/technology: Wheat (or barley, see above). This conclusion is supported by calculations (by Mikkel Overvad of DLG fodder wholesalers) using the linear programming tool "Bestmix" applying current prices and constrained supplies of food industry by-products.

Meat (NACE 01.2)
Market ties: -
Market segment: Not requiring meat from a specific type of animal (typically for minced meat).
Geographical market: Europe
Market trend: Increase
Production constraints: Meat from milking cows constrained by determining by-product (milk).
Affected supplier/technology: Pork production (as production costs are lower than for beef cattle).

Wood for fuel (NACE 02.01)
Market ties: -

Market segment: The supply and demand of wood is not as strongly connected as for many other materials, because of the long production time. Fuelwood is usually the by-product of construction wood, produced by premature thinning-operations of the wood-stands. Fuelwood can be produced from wood-diameters as small as 5-6 cm. The smallest parts are defined as wood residues, since they have no alternative, commercial use. Diameters from 10-11 cm can be sold for production of pulp.
Geographical market: Local
Market trend: Increasing, but decreasing compared to the expected supply of small dimensioned wood (FAO 1999), which means that the alternative fate for the small-dimensioned wood is to be left to decompose in the forest ecosystem.
Production constraints: None
Affected supplier/technology: Local wood-residues

Wood for pulp (NACE 02.01)
Market ties: -
Market segment: -
Geographical market: Regional
Market trend: Increase
Production constraints: None
Affected supplier/technology: Local small-dimensioned wood (diameters from 10-11 cm upwards).

Crude oil (NACE 11.1)
Market ties: -
Market segment: -
Geographical market: Global
Market trend: Increase
Production constraints: None
Affected supplier/technology: Heavy crude from Venezuela or Middle East, as they are the most competitive sources (those with the lowest extraction costs), and therefore are expected to increase their share in the global supply from 30% in 1991 to 45-57% in year 2010 (IEA 1994).

Aluminium (NACE 13.2)
Market ties: -
Market segment: -
Geographical market: Global (Schwarz 2000)
Market trend: Increase (Schwarz 2000)
Production constraints: None
Affected supplier/technology: Hall-Heroult with pre-baked anodes and point feeders (Gielen 1998a, Schwarz 2000). Separate electricity market: The aluminium production is unusual in being so electricity demanding that the localisation of the production plants is to a large extent determined by the availability of cheap sources of electricity. Thus, new smelters are typically placed in areas with unutilised hydropower and unutilised natural gas which is currently flared in connection to oil extraction. For example, recent expansion in smelter capacity has taken place or is planned in Iceland (hydropower and geothermic energy) and in Africa and the Middle East (hydropower and waste natural gas from oil extraction). Both the historical statistics published by the International Primary Aluminum Institute, and the projections for 2004 (Aluminum Association 1999) show that the high share of hydropower (56%) for primary aluminium production is surprisingly stable over time. Out of the publicly announced new plants, 57% is expected to be based on hydropower,

14% on natural gas and only 29% on coal (Aluminum Association 1999). Thus, the overweight of hydropower that has been prevailing in the average attributional-LCA data for aluminium production will also be the result of a market-based LCA-data for aluminium; see also modelling by Schwarz (2000).

Copper (NACE 13.2)
***Market ties:* -**
***Market segment:* -**
Geographical market: Global
Market trend: Increase (USGS 1999, 2001)
Production constraints: Pyrometallurgy constrained to sulfide ores and copper scrap. Some hydrometallurgical processes are also constrained to specific ore types.
Affected supplier/technology: Modern, raw material flexible (Caspersen 1998): Most recent plants built have been with solvent-extraction-electrowinning (a hydrometallurgical process) and 30% of new plants are expected to be of this type. Of the pyrometallurgical processes, for sulfide ores, the cheapest and most flexible technology that give an adequate quality is INCO/Outokumpu flash smelting with an energy consumption below 8.4 MJ/kg Cu. The Noranda process may compete in terms of energy consumption, but gives a lower quality and leaves more copper in slag.

Cadmium, Mercury, Lead (NACE 13.2)
***Market ties:* -**
***Market segment:* -**
Geographical market: Virgin material global; recycled material regional
Market trend: Decrease for cadmium and mercury (USGS 2001). For lead, the consumption increases, but mine production is stable or decreases as lead recycling is growing (ILZSG 2001). All three metals are co-products from polymetallic mines (zinc, gold, silver, copper) where demand for the co-product determines the output.
Production constraints: None
Affected supplier/technology: Waste deposits.

Vegetable fat (NACE 15.4)
***Market ties:* -**
Market segment: No specific fatty acid composition requested.
Geographical market: Global
Market trend: Increase (FAPRI 2000)
Production constraints: Soy oil constrained by demand for its co-product soy protein.
Affected supplier/technology: Rapeseed (canola) oil from EU or Canada (Vis 1998, European Commission 1997c, FAPRI 2000).

Dairy products (NACE 15.5)
Market ties: Suppliers are often bound by contract to a specific dairy.
***Market segment:* -**
Geographical market: Europe
Market trend: Small increase in Europe (European Commission 1997d), stable in Denmark (Fødevareministeriet 1996).
Production constraints: Milk production is constrained by quotas (European Commission 1997d), which means that the overall production volume is not sensitive to changes in demand. Thus, a change in demand will affect that application of milk, which is most sensitive to changes in supply.

Affected outlet/technology: Skimmed milk powder and butter, being the outlets with the lowest profit margin (Skak Jensen 2001). The underlying cause for this is that these products do not demand sophisticated skills or technology and are therefore produced many places. Furthermore, these products store well and are subject to EU interventions. A change in supply of skimmed milk powder and butter are not expected to lead to substitutions on the world market, since the consumption will be regulated through adjustments in prices. It should be noted that purchase of ecolabelled (ecological) milk will (eventually) lead to more production of ecological milk and less production of non-ecolabelled milk for milk powder and butter, while the purchase of non-ecolabelled milk just leads to less non-ecolabelled milk powder and butter. The net effect of ***choosing*** between labelled and nonlabelled milk is thus the difference between the two forms of agricultural production.

Wood and products of wood (NACE 20)
Market ties: -
Market segment: -
Geographical market: Depending on product requirement.
Market trend: Increase
Production constraints: None
Affected supplier/technology: Modern, often local: Drying plants with variable speed heat pumps (Hekkert & Worrell 1998).

Pulp, paper, board (NACE 21.2)
Market ties: -
Market segment: -
Geographical market: Local to regional, due to low value compared to weight. (Jordbrugsdirektoratet 1994, Danmarks Statistik 1997b, Lind 1998, and the references under ”market trend”).
Market trend: Increase (Joint ECE/FAO Agriculture and Timber Division 1996, FAO 1998, FAO 1999).
Production constraints: Recycled fibres constrained by availability.
Affected supplier/technology: Local, modern, based on softwood and light hardwood. The different pulping technologies have different demands for the raw material, depending on the amount of resin and the type of fibres (Tsuomis 1991, Bergstedt 1994). The neutralsulfite-process and the alkaline-process are best suited for broadleaved species; the alkaline-process can alternatively use straw. The sulfite- and the sulfate-processes can both use spruce and light broadleaves, and the sulfate-process can use pine too. Because of economy of scale, new plants are rarely built in Scandinavia or Germany (Karlson 1998) and instead existing plants are enlarged to meet the increased demand. Of historical reasons most paper plants in Germany use the sulfite-process, whereas most plants in Sweden use the sulfate-process. Since many of the trees in the new, fast-growing plantations in New Zealand and Asia consist of pine, for which the sulfate-process is best suited, this technology will most likely prevail for new plants in these areas.

Propylene (NACE 23.2)
Market ties: -
Market segment: -
Geographical market: EU
Market trend: Increase
Production constraints: Output of propylene from steamcracking constrained by relatively slower growth in demand for the co-product ethylene (Joosten 1998).

Affected supplier/technology: Fluid catalytic cracking off-gas cleaning (Joosten 1998).

Ethylene (NACE 23.2)
Market ties: -
Market segment: -
Geographical market: EU
Market trend: Stable to increase
Production constraints: None
Affected supplier/technology: Steam cracking of LPG or gas oil (Gielen et al. 1996).

Chlorine (NACE 24.13)
Market ties: -
Market segment: -
Geographical market: Europe
Market trend: Decrease (van Santen 1998b)
Production constraints: None
Affected supplier/technology: Old technology (mercury process).

Chlorine (NACE 24.13)
Market ties: -
Market segment: -
Geographical market: World, except Europe
Market trend: Increase (van Santen 1998b)
Production constraints: None
Affected supplier/technology: New technology (ion exchange membrane process).

Sodium hydroxide (NACE 24.13)
Market ties: -
Market segment: -
Geographical market: World
Market trend: Increase (van Santen 1998a)
Production constraints: Relatively lower growth in demand for chlorine provides a constraint on supply from chlor-alkali process.
Affected supplier/technology: Soda ash or sodium hydroxide from caustification of soda ash (van Santen 1998a).

Ammonia (NACE 24.15)
Market ties: -
Market segment: -
Geographical market: Europe
Market trend: Decrease. Surplus capacity in Eastern Europe.
Production constraints: None
Affected supplier/technology: Since energy is one of the main cost factors for producing fertiliser, it can be assumed that the least economic efficient plants have the highest energy consumption. The affected supplier can therefore be estimated to be an older plant in Eastern Europe with an energy consumption above 43 MJ/kg N, which is the highest national average energy consumption for the fertiliser industry in Europe (Worell et al. 1994, Patyk & Reinhardt 1997).

Fertiliser, in general (NACE 24.15)
Market ties: -

Market segment: -
Geographical market: Europe
Market trend: The global consumption of mineral fertiliser has shown a steady increase over the past decades (FAOSTAT), but the European market has experienced a decrease in the consumption of fertilizer due to environmental restrictions. The European Fertilizer Manufacturers Association (EFMA 1997, EFMA s.d.) forecasts that these trends will continue.
Production constraints: Supply of animal manure is constrained by the animal production being determined by other factors (the demand for other animal products, production quotas).
Affected supplier/technology: Artificial fertiliser. Plants producing mineral N-fertiliser can be based upon a variety of different technological and chemical processes (IFA, 1998). However, roughly they can be divided into two categories: plants based on imported ammonia or plants with a combined production of ammonia and fertiliser. The combined plants are typically found where the resource of natural gas is abundant, e.g. Norway. The combined plants have significant technical and economic advantage, since they avoid a process of transport and can use the CO2-emission as input in the production (Engstrøm 1998). Therefore the affected supplier (in the declining market) can be identified as one without own production of ammonia.

Rubber (NACE 25.1)
Market ties: -
Market segment: -
Geographical market: Global
Market trend: Increase
Production constraints: None.
Affected supplier/technology: Synthetic rubber from modern plants (Hekkert & Worrell 1998)

Bricks (NACE 26.4)
Market ties: -
Market segment: -
Geographical market: Local
Market trend: Decrease
Production constraints: None
Affected supplier/technology: Oldest local tunnel kiln.

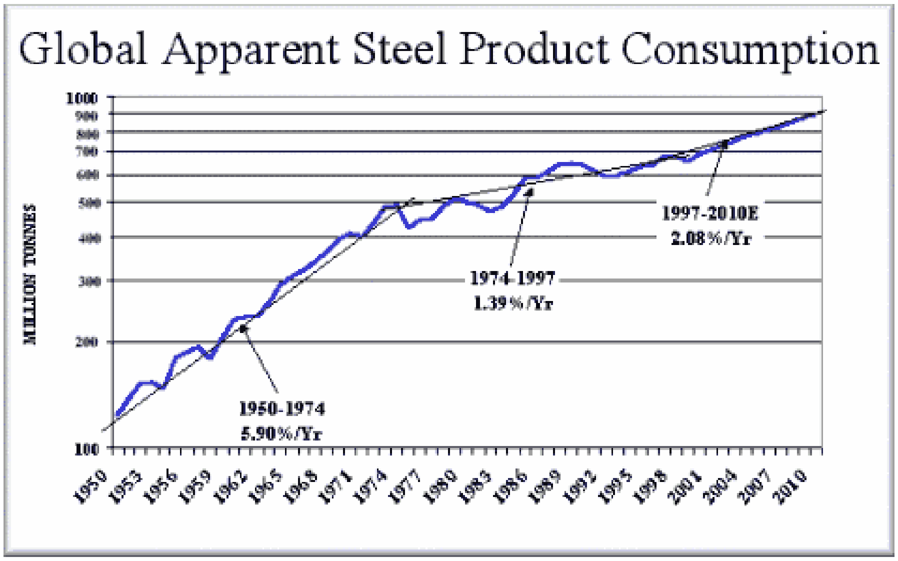
Cement clinker (NACE 26.5)
Market ties: -
Market segment: -
Geographical market: Local
Market trend: Decrease
Production constraints: Technology is raw material dependent.
Affected supplier/technology: Wet process in Denmark, since raw materials contain more than 20% water. Dry process in general.

Cement (NACE 26.5)
Market ties: -
Market segment: -
Geographical market: Local
Market trend: Decrease
Production constraints: Fly ash cements etc. constrained by raw material availability.

Affected supplier/technology: Portland. Older, local plants.

Steel (NACE 27.1)
Market ties: -
Market segment: -
Geographical market: Europe
Market trend: Increase. Trade statistics and forecasts are available from the International Iron and Steel Institute (http://www.worldsteel.org/) and World Steel Dynamics (http://www.worldsteeldynamics.com/).

Figur 4.2 (from World Steel Dynamics 2000)



Despite an increasing global trend, the European production of steel is stagnating, however not below the replacement rate of capital equipment.
Production constraints: Electric Arc Furnace technology constrained by availability of its main raw material (steel scrap).
Affected supplier/technology: Modern Basic Oxygen Furnace technology (Gielen & van Dril 1997).

Grid electricity (NACE 40.1)
Market ties: -
Market segment: Base load
Geographical market: Central Europe
Market trend: Increase (Eurostat 1997b, OECD 1997, European Commission 1996)
Production constraints: Nuclear and hydro based power politically constrained (European Commission 1995b, 1996, 1997a). Co-generating technology limited by the local demand for heat. The installation of co-generation is independent from the choice of technology for the general electricity market. Wind power is currently expanding its market share, but the development is still constrained by the availability of technical knowledge. In most of EU, lignite based power plants are no longer built due to emission quotas, especially the SO$_2$, NO$_x$ and CO$_2$ targets. An exception may be Greece, where lignite power plants produce most of the electricity supply without indication of decline (Eurostat 1997a).
Affected supplier/technology: ***Coal-based technology. This conclusion is based on the calculation of production costs shown in the table below. The production costs***

are composed of operation and maintenance costs, fuel costs and depreciation and interest on capital goods. Operation and maintenance costs and capital goods are taken from Energistyrelsen (1995) and data on fuel costs are from Larsen (1997). The calculations are made for proven technologies, relevant for new plants. The results are verified with data published by Hammar (1997). Calculations have been made for such technologies only, which may have a potential to be the marginal electricity source following the considerations in the above sections. Due to fluctuation in demand, power plants operate on average at less than full capacity. In the calculations, 50% capacity utilisation is assumed. The efficiencies of the plants are for electricity production only, since co-production of heat is not relevant for a marginal power plant, for reasons stated above.

Fuel type	Plant type	Efficiency	Life time	Product per year	Capital investment		Operation and maintenance		Fuel			Total cost
	MW	%	Yrs	MWh/yr	DKK/MW	DKK/MWh ***	% of investment per year	DKK/MWh	Calorific value in MJ/kg	Price in DKK/kg	Cost in DKK/MWh	DKK/MWh
Hard coal	400	47	30	1.75E6	8E6	110	3.2	59	25.1	0.28	84	250
Nat. gas	15	36	25	6.6E4	5E6	82	2.5	59	39.6 (MJ/m^3)	1.3 (/m^3)	330	470
Nat. gas	250 CC*	54	30	1.1E6	5E6	68	2.5	34	39.6 (MJ/m^3)	1.3 (/m^3)	220	320
Heavy fuel oil	15	43	25	6.6E4	6E6	99	-	100**	40.6	0.69	140	340
Bio-mass	250* CFB	45	30	1.1E6	8E6	110	4	73	17.5	0.53	240	420

* CC: Combined Cycle in which a natural gas driven turbine and another turbine driven from steam produced from the exhaust gas of the gas turbine. CFB: Circulating Fluid Bed. Technology at experimental stage.

** Authors' estimate. Total cost 250-320 DKK/MWh according to Hammar (1997) excl. capital goods.

**** Includes a factor 1.8 on the values from the previous column to take into account 6% interest on the investment over 20 years.*

The calculation is most sensitive for the fuel costs, where the gas price may be set too high in the above calculations. Furthermore, due to the lower capital costs required, gas fired plants may also be the preferred technology under periods of high interest rates and insecurity. The current deregulation also favors technologies with low investment costs, as has been seen after the deregulation in the U.K. (DTI 1998). Furthermore gas fired plants better fulfil the requirements of the electricity networks for ability to adjust output quickly on a minute-to-minute basis (Dienhart et al. 1999). Therefore, it may be recommended to apply gas-fired technology in a sensitivity analysis.

Grid electricity (NACE 40.1)
Market ties: -
Market segment: Base load
Geographical market: Nordic countries
Market trend: Increase
Production constraints: As above + emission limits for SO_2, NO_x (and CO_2) that do not leave room for much expansion of coal based power plants. Surplus coal based capacity.
Affected supplier/technology: Coal-based technology within existing capacity likely to cover demand for next 10 years. Any new power plants planned are natural gas fired (Nordel 1996). This is also confirmed by a recent study

based on a dynamic model of the Nordic electricity system (Mattsson et al. 2001).

Grid electricity (NACE 40.1)
***Market ties:* -**
Market segment: Base load
Geographical market: Greece
Market trend: Increase
Production constraints: Nuclear and hydro power politically constrained
Affected supplier/technology: Lignite-based technology

Water supply (NACE 41.00)
Market ties: Drinking water is supplied through a regional water supply. In Copenhagen, the extraction of groundwater is politically controlled by the counties, but within this constraint, the Copenhagen Water Supply choose between a variety of technologies.
Market segment: Like electricity, water consumption fluctuates on a daily and yearly basis, but because of storage capacity in ground water basins and water towers, the market is not temporally segmented, except for very dry periods where the base load supply may be supplemented by cleaned surface water. In principle, tap water and secondary water may be distinguished, but requires separate piping, which makes the latter prohibitively costly in most applications (see below).
Geographical market: Greater Copenhagen.
Market trend: Increasing relative to the decrease in supply capacity from current technology, which is pumping of naturally generated ground water (Miljø- og Energiministeriet 1998). Therefore new technology (most preferred, unconstrained technology) must be installed.
Production constraints: Extraction of naturally generated ground water is presently the most used technology, and in the Copenhagen area ground water accounts for 94-99% of the water supply each year (Passow 1998). This technology is constrained by the renewal rate of high quality ground water. In the Copenhagen area as much as 2.5 times the sustainable amount is pumped (Albrechtsen et al. 1998) and in many regions the resource is threatened by percolations from industry, agriculture and gardens. Ground water only needs a few cleaning operations: filtering, aeration, oxidation etc. Water of poorer qualities (polluted ground water and surface water) can be cleaned to an acceptable quality through different chemical processes. The capacity is however, still very little used, partly because the cleaning process involves chlorination, a process leaving an off-taste. Presently this is not considered politically acceptable for base load supply. Ground water can be artificially produced when surface water is irrigated on fields. This technology is called infiltration, and can utilise much poorer qualities of surface water, since e.g. organic compounds are effectively filtered by the soil. A pilot plant made by the Copenhagen Water Supply and the Technical University of Denmark shows very positive results (Gardarsson 1997), and the Copenhagen Water Supply assumes it is a matter of short time before more infiltration-fields are established (Passow 1998). This technology may eventually become constrained by its area requirement. Rainwater can be collected from roofs of buildings. The Danish Ministry of Environment and Energy estimates the potential to 2.3 E08 m^3 of water. This potential is almost unused, and the amounts are led through the sewerage system together with wastewater. The rainwater cannot be used directly for drinking, but must either be cleaned or only used for washing machines and toilets. The existing plants are local, supplying the house beneath the roof, and mostly the quality problem is

overcome by installation of a separate pipe system in the house. The technology is most relevant for single-family houses, where the roof area is relatively bigger and the pipes easier to change than in apartment houses. The technologies mentioned so far are all ultimately constrained by the overall amount of water supplied by local precipitation. When encountering this constraint we are left with two options: Long distance transport and desalination, both practically unconstrained. In Copenhagen, the uses of these technical possibilities are constrained by the political goal to keep the water supply on a local basis (Lund 1993, Sydvatten 1998).

Affected supplier/technology: Production costs have been obtained for Copenhagen (see table) and may not apply globally. However, the factors influencing the productions costs are likely to be universally valid. From the table, the most likely technology affected in the Copenhagen situation is artificial ground water production. If this technology becomes constrained by the amount of land available for the infiltration process, the decision makers have to make a trade-off between price and quality standards. If price is most important the new technology will be cleaning of local surface water, and if more production volume is needed the desalination process or cleaning of polluted ground water can be taken into use. Cleaning costs (or alternative piping for rain water) may run very high - even higher than the costs of desalination - depending on the degree of pollution. If quality requirements are more important than the price, or when local water sources fail, long distance transport becomes relevant. For the Danish capital there is adequate amounts available in a large lake in Sweden, only 100 km away, although part of the pipeline will be underwater in the sound dividing Denmark and Sweden. For countries where the transportation distance is longer or more difficult, desalination is the ultimate option. Due to recent advances in desalination technology, the price is no longer prohibitive and often competitive to chemical treatment of polluted water or collection of rainwater. For industrial use, desalination may even be the cheapest option, since water taxes may be avoided (Hinge & Salemsen 1996). As long as the demand of water can be met from other sources, collection of rainwater is irrelevant because of the prohibitively high price.

	Depre-ciation	Fixed costs	Clean-ing costs	Other variable costs	Total costs
	(DKK/m3)	(DKK/m3)	(DKK/m3)	(DKK/m3)	(DKK/m3)
Artificial ground water production	0,3-2,0	0,7-1,5	0,5-1,2	0,5-0,8	2-5
Cleaning of local surface water (lakes)	0,3-2,0	0,7-1,5	1-3	0,5-0,8	3-7
Desalination	1-5	0,2-0,6	-	3 - 8	4-13
Cleaning of polluted ground water	0,3-2,0	0,7-1,5	2-10	0,5-0,8	4-14
Long distance transport	2,2	1,5	0,5	0,8-1	5-5,2
Collection of rain	25-82	0,5	0	0,4	26-83

Data on depreciation are provided by a private drilling-firm and the statistics of the Danish Water Works Association (VandSchmidt 1998, Danske Vandværkers Forening 1997). Fixed costs, cleaning and other variable costs are estimated from a technical report on ground water valuation and personal communication with employees at the Copenhagen Water Supply (COWIconsult 1995, Passow 1998, Als 1998). Cleaning of surface water costs 1-2 DKr, while the costs for cleaning polluted ground water can vary considerably depending on the actual quality. These data are from Kemp & Lauritsen (1995) and two local water works (Regnemark Waterworks 1998, Gentofte Waterworks 1998). Artificial production of ground water through infiltration gives additional costs for irrigation and land use. Data on infiltration costs for artificial ground water production is supplied from the pilot plant of the Copenhagen Water Supply and the Technical University of Denmark (Gardasson et al. 1997). Desalination costs are estimated on basis of Ribeiro (1996). If water is to be transported from water works in other geographical regions, there will be additional costs for construction and maintenance of a pipeline and costs for pumping. These costs can vary considerably depending on the nature of the subsoil, the needed capacity and the slope of the distance. Construction costs alone can vary from a mere 140 DKK/meter to 13.000 DKK/meter. Data here are based upon an internal calculations performed by the Water Supply of Copenhagen to assess the possibility of supplying water to Copenhagen from a distance of approximately 100 km from a Swedish lake (Lund 1993) with standard costs for maintenance (COWIconsult 1995) and operating costs roughly estimated by Sydvatten (1998). The cost of collecting rainwater from roofs is estimated by Albrechtsen et al. (1998). Most of the investment for collection of rain is for changing the piping, and the cost depends very much on the type of house. An alternative to changing the pipes is to filter and clean the rainwater, but the cost for this is estimated to be higher, mostly because of control-costs.

Waste treatment (NACE 90.00)
Market ties: -
Market segment: Non-separated household wastes.
Geographical market: Local (Europe outside Denmark).
Market trend: Increase
Production constraints: In Denmark, legislation prohibits landfilling of combustible waste. Outside Denmark, waste incineration capacity is fully utilised, although expanding (Ekvall & Finnveden 1998).
Affected supplier/technology: Landfilling (Ekvall & Finnveden 1998).

5 Method for handling co-products[15]

When a process or product system in an LCA is related to more than one product, it presents a problem: how should its exchanges, such as the resources consumed and the releases generated, be partitioned and distributed over the multiple products?

The allocation of these multiple products, known as "co-products", has been one of the most controversial issues in the development of the methodology for LCA, as it may significantly influence or even determine the result of the assessments. It has been seen as so central a procedure that it is often (even in the International Standards Organization standard on life cycle assessment, ISO14040) nick-named "allocation" as if it was the only allocation problem in LCA[16].

Allocation is the partitioning and distribution of an item over several other items. Co-product allocation is the partitioning and distribution of the exchanges (e.g., inputs and outputs) of a multi-product process over its co-products. The co-product allocation problem is parallel to the cost allocation problem, which has been extensively treated in the economic literature (a review pertinent to LCA is provided by Frischknecht 1998). However, while cost allocation is primarily an accounting tool where the different methods can be said to have each their advantages and disadvantages from the view of different decision makers focusing either on issues internal to their business or on direct business-to-business relations. In contrast, LCA begs for a solution that models as closely as possible all the external consequences of a potential change in demand for one of the co-products.

The idea that co-product allocation can be avoided by system expansion has been put forward by Tillman et al. (1991) and Vigon et al. (1993) with respect to waste incineration, and more generally by Heintz & Baisnee (1992). System expansion is performed to maintain comparability of product systems in terms of product outputs, through balancing a change in output volume of a co-product that occurs only in one of the product systems, by adding an equivalent production in the other systems (or more elegantly and correctly by subtracting the equivalent production from the one system). For example, in the case of an LCA involving chlorine gas co-produced with sodium hydroxide used in another product system, the system is expanded with an alternative stand-alone production of sodium hydroxide, and the environmental releases and resource consumption of this alternative production is then subtracted from the system using the chlorine gas.

System expansion was given a prominent place in the procedure of ISO 14041, where it reads in section 6.5.3: "Step 1: Wherever possible, allocation shall be avoided by: 1) dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these

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[15] An early version of this chapter was published as Weidema 2001a.

[16] Other allocation problems in LCA include the allocation of products over different functions, the allocation of aggregated environmental data over individual processes, the allocation of emissions over different environmental compartments, and the allocation of emissions over parallel or serial environmental mechanisms.

sub-processes; 2) expanding the product system to include the additional functions related to the co-products…”.

Although avoiding allocation is seen as the preferable option, it has generally been regarded as impossible to expand the system in all cases. Therefore, other options have been maintained, especially the allocation according to the revenue or gross margin from the products, a procedure commonly applied in cost accounting (Huppes 1992). Older studies used simple physical allocation criteria such as the relative mass or exergy of the products, but these criteria have generally been discredited for lack of justification (Huppes & Schneider 1994), except in attributional, non-comparative LCAs, where they may still be used as a proxy for revenue.

The following four obstacles to system expansion can be seen as part of the reason why this option has not generally been applied as a way to avoid allocation:

1. In attributional LCAs, there is typically no possibility for system expansion. Attributional studies typically seek to describe a status-quo situation, in which there are no changes in production volume. This obviously excludes the possibility of system expansion, because an expansion involves balancing a change in output volume of a co-product in one system with an equivalent change in the other systems to be compared, in order to maintain comparable product outputs from the systems. The distinction between attributional and consequential studies and its important consequences for the methodology (including the handling of co-products) has only recently been clarified (see section 1.2). It is still common to see attributional studies applied for decision support and a mix of methodologies and justifications without clear reference to the attributional or consequential nature of the study.
2. It has been regarded as too difficult, too uncertain, or even impossible to identify which processes are affected when balancing a change in demand for (or supply of) a specific co-product.
3. Because a system expansion may involve processes that also have multiple products, it has been suggested that there are situations where system expansion would be impossible because it would involve an unending regression.
4. When a by-product does not substitute for another product, system expansion may be regarded as incompatible with the requirement that compared systems must have identical functions.

In this chapter, it is shown that allocation can (and shall) always be avoided in consequential LCAs. In attributional LCAs, it is not possible to express an imperative regarding what allocation procedure to apply, but avoiding allocation may still be an option. We reach this conclusion by demonstrating how to overcome the four obstacles listed above:

1. By distinguishing clearly between attributional and consequential studies, it is possible to distinguish between the situations in which system expansion is both possible and mandatory (consequential studies) and the situations in which system expansion is irrelevant or at least optional (attributional studies).
2. In chapter 4, it was shown that it is always possible, and seldom difficult, to identify the processes affected by a change in demand. The uncertainty of this determination, and the fundamental uncertainty of future market situations, are inherent to the method, but can be neither a theoretical nor a practical argument against system expansion.

3. The problem of unending regression is eliminated by applying the method from chapter 4, which provides clear cut-off criteria (either a process is included or excluded from the studied system) and reduces the number of processes that may possibly be involved in a system expansion (for details, see section 5.8).
4. It is shown that by-products practically always substitute for other products, and even when this may not be the case, the studied systems are still comparable.

In the following sections it is demonstrated how system expansion is performed, with a number of examples. Special emphasis is placed on issues that have earlier been in focus of the allocation debate: joint production of e.g. chlorine and sodium hydroxide, zinc and heavy metals; the handling of “near-to-waste” by-products; and credits for material recycling and downcycling. It is shown that all the different co-product situations can be covered by the same theoretical model and the same procedure. Separate sections deal with the issues of uncertainty, co-product allocation as a special case of system expansion, and comparison to the procedure of ISO 14041.

5.1 Why system expansion is the preferred option for handling co-products

To study correctly the effects of a potential product substitution in consequential, comparative LCAs, it is necessary that the studied product systems:

- are comparable, which means that they must provide the same functions, thus reflecting the substitution that is really expected to take place (Chapter 3),
- include all significant processes that are affected by the potential product substitution (Chapter 4).

In general, these two conditions are not fulfilled by allocation. First, allocation typically involves a more or less arbitrary partitioning of the co-producing process over its co-products, without consideration of the extent to which a change in the amount of these co-products actually affects the functional output and other exchanges of the co-producing process. Secondly, allocation ignores the effects that a co-product may have on the further fate of the other co-products, i.e. displacement effects and additional treatment of the co-products before displacement takes place.

Thus, traditional co-product allocation only fulfils the above two conditions in those particular instances where the allocation factors are chosen to reflect the way the co-products actually affect the co-producing process and where there are no significant effects on the further fate of the other co-products. In such instances, allocation may be regarded as a special instance of system expansion, as described in section 5.10.

The above two conditions are fulfilled by system expansion, because any process, which will be affected by a change in the amount of co-products, is included in the studied product systems, and it is ensured that all systems yield comparable product outputs, by subtracting or balancing processes that do not occur in all of the compared systems (for details, see the procedure described in later sections). This is the rationale for preferring system expansion to allocation for handling co-products in prospective LCAs.

In a non-comparative, attributional LCA, the preference for system expansion (as in the ISO procedure) still leads to a reasonable result, when the study is understood as an analysis of hypothetical historical changes like: What ***would*** have happened if this product had not been introduced or if this product had been produced instead of this? In this case, historical market data can be used to calculate hypothetical system expansions and to show what the results would have been of a prospective LCA if it had been produced at that historical moment.

5.2 Theoretical model for system expansion

System expansion is illustrated in figure 5.1 showing a co-producing process with one determining co-product (product A); that is, a co-product that determines the production volume of that process. This is not necessarily the co-product of interest to the specific life cycle study. In figure 5.1, just one dependent co-product is shown, but in practice there may be any number of co-products.

That a product is determining for the production volume of a process is the same as saying that this process will be affected by a change in demand for this product, as identified by the procedure in chapter 4.

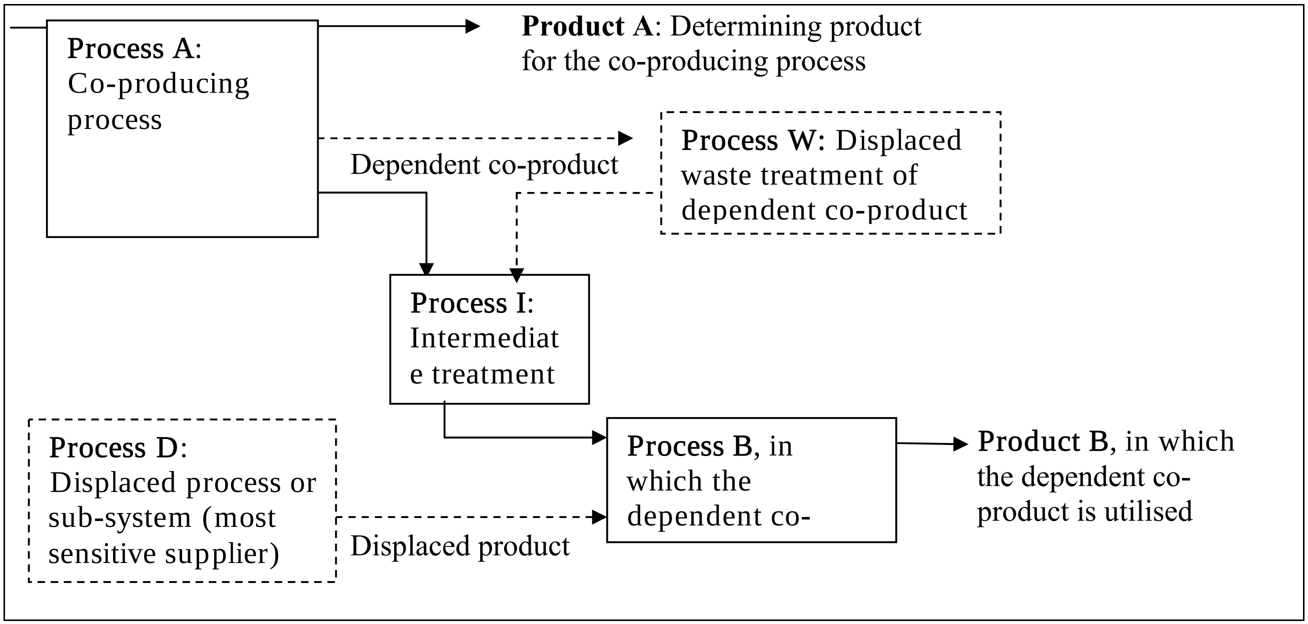

Figure 5.1 Model for describing system expansion and delimitation for joint production, valid both when product A and product B is the product used in the life cycle study.

Performing a system expansion in relation to joint production is to answer the question: ***How will the production volume and exchanges of the processes in figure 5.1 be affected by a change in demand for the co-product that is used in the life cycle study?***

Because the environmental exchanges are generally linked to the production volumes, the answer to this question will also provide a solution to the allocation issue. This question is equally relevant when the co-product used in the life cycle study is the determining product for the co-producing process (A) and when it is the product in which the dependent co-product is utilised (B).

A complete identification of changes in production volume as a function of change in demand would require an economic model for all the involved processes and product flows. The procedure presented here involves the simplifying assumption that a change in demand for a dependent co-product does not affect the production volume of the co-producing process[17].

Under this assumption, the answer to the above question can be summarised in three rules[18]:

1. ***The co-producing process shall be ascribed fully (100%) to the determining co-product for this process (product A).*** This follows logically from product A per definition being the co-product, which causes the changes in production volume of the co-producing process.

2. ***Under the conditions that the dependent co-products are fully utilised, i.e. that they do not partly go to waste treatment, product A shall be credited for the processes that are displaced by the dependent co-products. The intermediate treatment shall be ascribed to product A. If there are differences between a dependent co-product and the product it displaces, and if these differences cause any changes in the further life cycles in which the dependent co-product is used, these changes shall likewise be ascribed to product A.*** This rule follows from the fact that – under the stated condition – both the volume of intermediate treatment and the amount of product which can be replaced, is determined by the amount of dependent co-product available, which again is determined by the change in production volume in the co-producing process, which is finally determined by the change in demand for product A. It follows from this rule that product B is ascribed neither any part of the co-producing system, nor any part of the intermediate treatment. When studying a change in demand for product B, this product shall be ascribed the change at the supplier most sensitive to a change in demand (identified by the procedure described in chapter 4), i.e. the same process, which is displaced by a change in demand for product A (but see also rule no. 3). If the condition stated in rule no. 2 (that the co-product is fully utilised in other processes) is not fulfilled, rule no. 3 applies.

3. ***When a dependent co-product is not utilised fully (i.e. when part of it must be regarded as a waste), the intermediate treatment shall be ascribed to the product in which the dependent co-product is used (product B), while product B is***

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[17] This is parallel to the implicit assumption of the procedure in chapter 4 (see section 4.1) and as suggested there, separate scenarios should be applied when this assumption is regarded as too simplified (especially as it may change over time, depending on location, and depending on the scale of change). This implies that when more than one joint product is found to be determining within the studied scale or geographical or temporal horizon, a scenario may be calculated for each joint product that may be determining. These scenarios may be kept separate or added up to form averages, weighted in proportion to the influence of the different co-products. Such a weighted average of scenarios have close relations to an allocation of the co-producing process (see section 5.9).

[18] In an early version (Weidema 2001a), a fourth rule was included, covering the situation when a dependent co-product does not displace any other product. With the current wording of the rules, this situation is now regarded as a special case of rules 2 or 3, depending on whether the co-product is fully utilised or not; see also section 5.5.

credited for the avoided waste treatment of the dependent co-product. This follows from the volume of the intermediate treatment (and the displacement of waste treatment) in this situation being determined by how much is utilised in the receiving system, and not by how much is produced in the co-producing process. Another way of saying this is that in this situation, process I (the intermediate treatment) is that supplier to process B, which is most sensitive to a change in demand for product B.

Figure 5.2 illustrates the implications of the three rules, in terms of how the different processes in figure 5.1 are ascribed to the two products A and B.

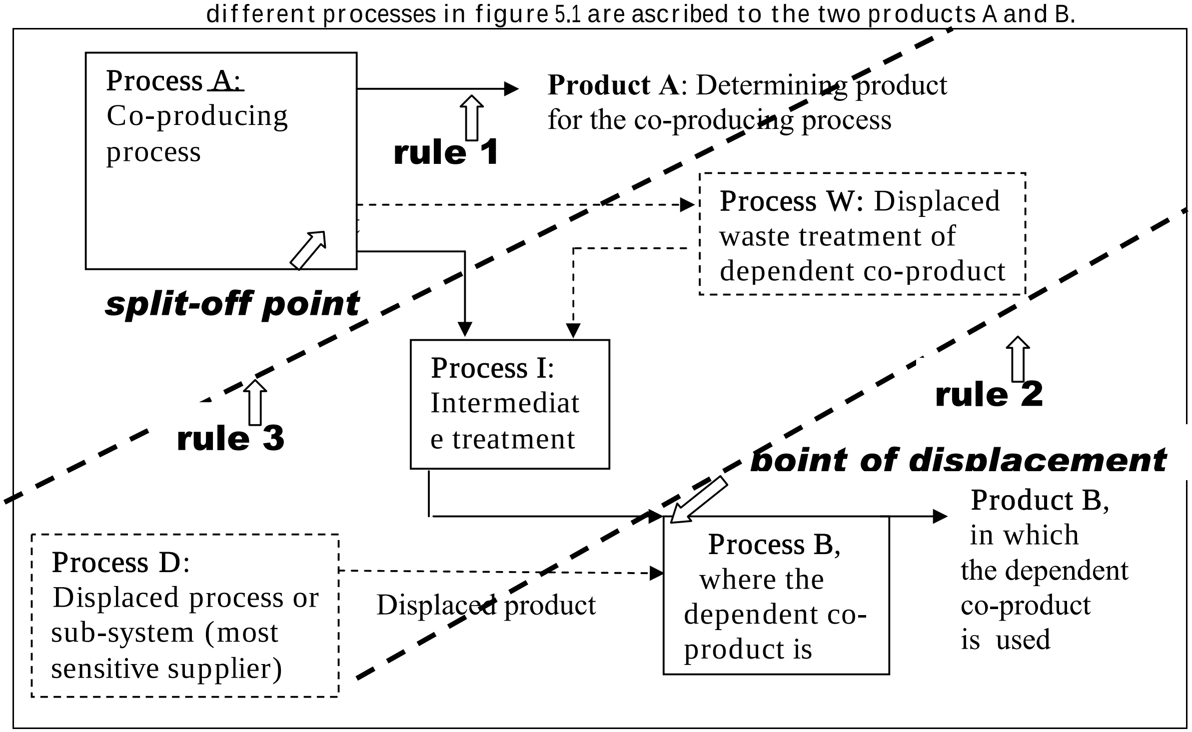

Figure 5.2 Illustration of the three rules and their cut-off implications. Rule 1 implies that process A is always fully ascribed to the determining co-product. Rule 2 - which is applicable when the dependent co-product is fully utilised - implies that product A is ascribed all processes until the point of displacement. Rule 3 - applicable when the dependent co-product is not utilised fully - implies that product B is ascribed all processes after the split-off point.

It may at first sight appear counter-intuitive that the intermediate process is ascribed to product A when product B utilises all of a dependent co-product, while the process is ascribed to product B when only part of the co-product is used in product B. This is a reflection and a good illustration of the difference between the (more intuitive?) attributional perspective that focus on the average behaviour (full utilisation or not) of the intermediate process rather than on the consequences of this full utilisation for the ***changes*** in the volume of the intermediate process when demand for product B changes, which is the focus of the consequential approach upon which the three rules are based.

5.3 A procedure for handling co-products

Figure 5.3 presents a procedure for handling co-products in the form of a flow-chart. An initial distinction can be made between ***joint production***, where the relative output volume of the co-products is fixed, and ***combined production*** with independently variable output volumes (Huppes 1992). For the latter type of production, allocation can be avoided simply by modeling directly the consequences of a change in the output of the co-product of interest (that which is used in the product system under study) without change in the output of the other co-products. This situation is dealt with in step 1 of the procedure. The remaining part of the procedure (steps 2 to 4) deals with the situation of joint production where allocation can only be avoided through system expansion.

For combined production, a physical parameter can generally be identified, which - in a given situation – is the limiting parameter for the co-production. It is the contribution of the co-product of interest to this parameter, which determines the consequences of the studied change. In the guideline (Weidema 2003), two examples are provided of this: treated surface area of product plus border area in a combined surface treatment, and weight or volume in different situations of combined transport. Here we add an example of a combined freezer/refrigerator and the classical example of combined treatment of several wastes in the same treatment plant (e.g. landfill or incinerator):

Example:

Refrigerators and freezers are often built as combined equipment to reduce the heat loss, and take advantage of savings in insulation and casing. An additional need for refrigerator space may be covered by adding a separate refrigerator, but more rationally the existing combined option may be substituted by another combined option in which the refrigerator space is larger relative to the freezer space. Here we assume that the old equipment is anyway up for replacement or can be utilized in another context, since the old equipment should else be included in the calculation. The energy requirement of the marginal refrigerator space can be determined from comparing the two options, or more generally by identifying the relevant physical parameter that determines the relative energy consumption. Also here, the physical parameter can be identified as the co-called "temperature adjusted volume", which can be calculated as: $V_{adj} = V_c * (t_r - t_c)/(t_r – 5\ °C)$, ***where*** V_c ***is the volume of the compartment,*** t_r***, the room temperature,*** t_c ***the temperature of the compartment, and 5 °C is the reference temperature. Thus, it is the contribution to*** V_{adj} ***that determines the energy requirement of the additional refrigerator space.***

Example:

In combined waste treatment, many emissions depend on the composition of the incoming waste. For example, the emissions of cadmium will be in proportion to the amount of cadmium in the incoming waste. Thus, adding a cadmium-containing item will increase the emissions of cadmium by this amount. The same straightforward logic applies to the creation of incineration ashes, which depends on the ash content of the different incoming wastes. However, some emissions are not dependent on the composition of the incoming waste. Classical examples from incineration are NO_x, which is formed in the combustion chamber, and dioxins, which are formed mainly in the ”exhaust cleaning” processes. The formation of NO_x depends mainly on the combustion temperature, and while the formation of dioxins has some connection to the occurrence of elements like carbon and chlorine, many other elements act as catalysts in the process. In principle, it is possible to add different kinds of waste and measure the change in formation of NO_x and dioxins, thus reaching an understanding of the relations between the type of waste and the emissions. However, as long as the chemical reactions and their determining parameters are not fully understood it is most reasonable to assume that the emissions of NO_x and dioxins will change in proportion to the overall limiting parameter of the combustion process. Waste incinerator capacity is generally limited by the weight of incoming waste, which means that the emissions of NO_x and dioxins should change in proportion to the weight of the treated waste.

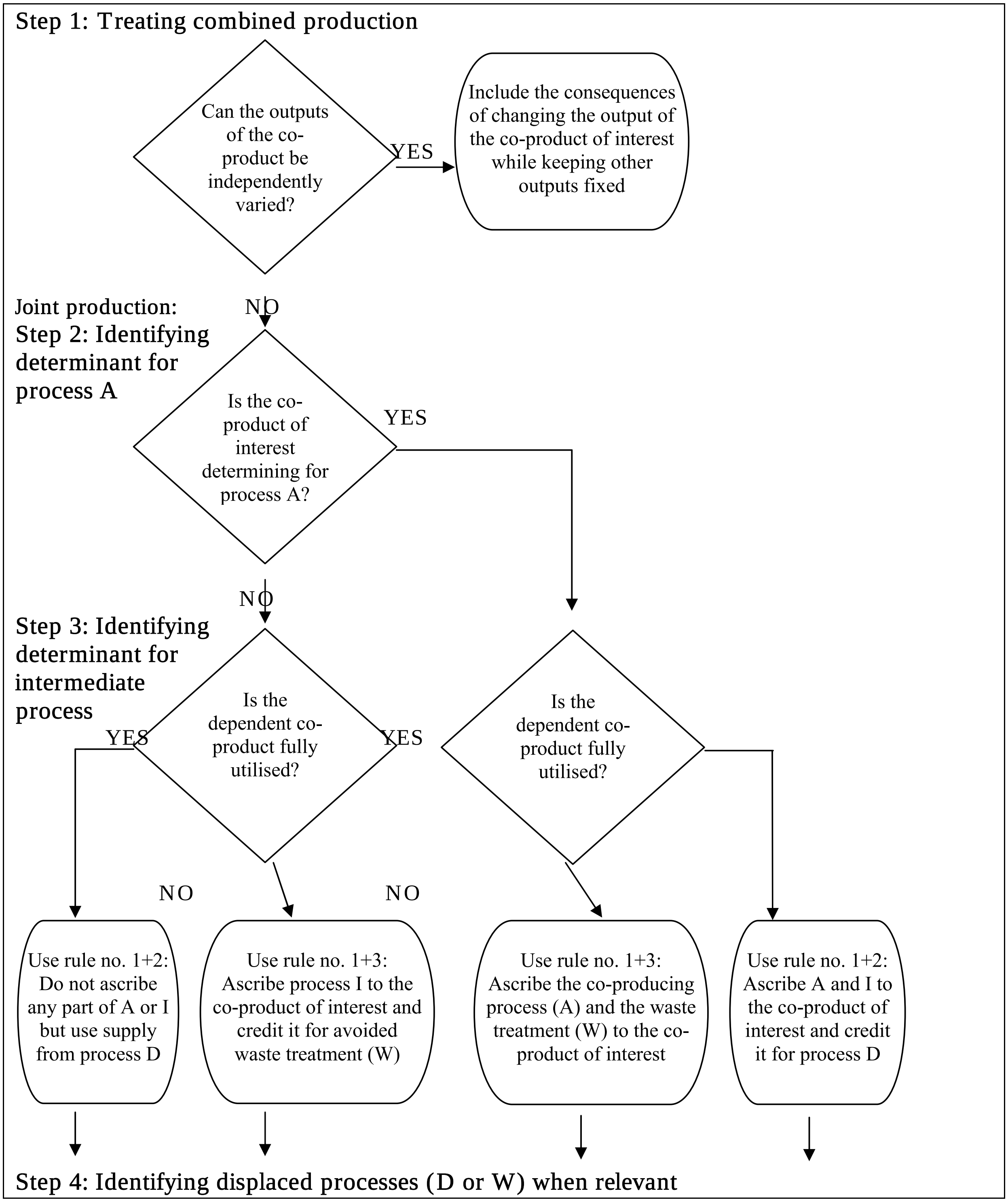

Figure 5.3. Decision tree showing the 4-step procedure for handling co-products.

The limiting production parameter may depend on the original situation. Therefore, it is essential to describe both the original situation in terms of the relative outputs of the co-products before the studied change, and the production parameters that in this situation are determining the changes in the exchanges of the combined production. This is even more obvious when the output of the co-products can only be varied within certain limits, that is, when the production cannot be separated completely. In many production processes where one raw material is used to produce several outputs, the production parameters can be adjusted to give different relative yields of the co-products, but only within certain limits. When operating close to such a limit, the consequences of the studied change may be ambiguous, and this should be reflected in the modeling and its results.

Example:
In oil refining, the output of bitumen (asphalt) varies between 7% and 79% depending on the origin of the raw oil. Thus, for each individual raw oil type, the output of bitumen is not variable, but for refineries as a whole, there is some flexibility to meet changes in the demand for bitumen, as long as the demand as a whole does not fall below 7% of the demand for the remaining refinery products. If the demand falls below this limit, bitumen could become a waste product (although some of it can be reprocessed for combustion purposes in the form of tar-sand and orimulsion), and this alternative situation should then be modelled in the LCA.

Example:
On a milk farm, the outputs of milk and meat can be individually varied within certain limits. The milk output can be regulated e.g. by changing the fodder composition, and the amount of meat output can be regulated through the rate of replacement of the milking cows. However, there are both physical limits to the maximum milk yield per animal and the minimum replacement rate. The output of meat will be determined by the replacement rate, which gives the desired milk production, not by the demand for meat. Thus, an additional output of meat can only be obtained by increasing the amount of calves raised for meat, an additional production not originally included when studying a milk producing system.

As already suggested by the last example, some productions may appear as allowing individual variation in output, but when subjected to a closer analysis it is only possible to keep the output of the other co-products constant by adjusting sub-processes not involved in the original production. Thus, what appears at the superficial level to be a case of individually variable co-products may in fact be a joint production requiring a system expansion (steps 2-4 of the procedure, see below).

Example:
If an oil refinery is regarded as a black box, the outputs of different fuels, olefins and other refinery fractions may be individually varied, so that practically any desired relation between the outputs can be obtained. The only fixed fractions are refinery gas and bitumen. However, when having access to data for the individual processes within the refinery, it becomes clear that this flexibility in outputs is achieved by allowing simultaneous changes in a large number of individual processes. Looking specifically at the major olefins: ethylene and propylene, the main production route is steam-cracking which yields ethylene in a relatively high proportion. The specific proportion is fixed for each raw material, so that the relative outputs of the two

olefins can be varied by shifting between a raw material that yield practically only ethylene (ethane) and those raw materials (LPG, naphtha, and gas oil) that yield increasingly larger proportions of propylene yields (42, 53 and 61% of the ethylene yield respectively). However, also another production route exists that yields more propylene than ethylene. This secondary route uses the off-gases from fluid catalytic cracking (FCC). Thus, a change in the demand for one of the two products may cause either a shift in raw materials for steam cracking or a shift in volumes between steam cracking and FCC offgas-cleaning, until a new balance is found that satisfies the current demand. Which of these options will be chosen depends on the price relations between the options, and the constraints on raw material availability and the demand for the other co-products (the mentioned raw materials also yield increasing outputs of C_4 and BTX fractions along with the increase in propylene). The described changes can be modelled as a system expansion within the refinery, as shown in Weidema (2003).

5.4 Identifying a product as determining for the volume of the co-producing process

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.

Identifying a product from a joint production (to keep it short, such a co-product will simply be called ***a joint product*** in the remaining part of this section) as determining for the production volume of the co-producing process is the same as showing that the co-producing process will be affected by a change in demand for this specific co-product (which we will then call ***a determining co-product*** for short). When the co-producing process is identified as the affected process by using the procedure in chapter 4, we have in fact at the same time identified the co-product under study as being a determining co-product.

For a co-product, the crucial point in the procedure in chapter 4 is the identification of the other co-products as a production constraint. The production volume of the co-producing process is constrained by the demand for the determining joint product(s). Independently variable (combined) co-products cannot provide a constraint and may be simultaneously determining (as described in the previous step).

In this section, it is explained:

- how to identify the determining co-product,
- why there is typically only one of the joint products that is determining the production volume of the co-producing process at one given moment,
- why the determining co-product is not necessarily the co-product, which yields the largest economic value to the process, and
- why the determining co-product is not necessarily the co-product, which has the largest change in demand.

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 adequate to document that a change in demand for the joint product leads to a change in revenue for the co-producing process.

However, as already discussed in section 2.4, the default assumption in life cycle assessment is that suppliers are price-takers and the long-term market price of a co-product is therefore typically determined by the long-term marginal production costs of the alternative production route for this co-product, if such an alternative route exists. As long as the 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, there is typically only one of the joint products that is determining at any given moment. This understanding can be further elaborated into the following two conditions:

To be a determining co-product, a joint product (or a combination of joint products in which the co-product takes part) shall:

i. provide an economic revenue that is in itself adequate reason for changing the production volume

and

ii. have a ***larger*** market trend (change in overall demand) 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, the co-product with the ***smallest*** market trend is determining the ability of the combination to influence the production volume.

The last condition can be illustrated by a theoretical process with the 4 joint products A,B,C and D, having the following revenues and market trends:

Co-product	Marginal revenue	Market trend
A	10	small
B	6	medium
C	5	large
D	1	large

Note that the stated market trends and revenues are relative to the normalised output volumes of the co-producing process, which means that differences in the actual physical quantities have already been eliminated. At a marginal production cost for the co-producing process of 9, only one co-product (A) can provide adequate revenue to change the production volume alone. Product C cannot alone influence the production volume, in spite of the large market trend for this product. However, the combination B and C also fulfil the condition of providing adequate revenue. The possible influence on the production volume from this combination is determined by the smallest of the market trends of the products in the combination. This is the medium trend of product B. Because this is still larger than the trend of product A, product B becomes the co-product that determines the production volume.

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.

Example:
Approximately 90% of all primary cadmium is a co-product of zinc extraction. Mercury, lead, and sulfur are also produced as co-products of zinc extraction. The demand for zinc is increasing moderately (Henstock 1996) while the demand for the heavy metals cadmium, mercury, and lead is stagnating mainly due to environmental regulations. The supply of cadmium from compulsory take-back and recycling of cadmium-containing products means that some primary cadmium is currently deposited (landfilled) and the same situation can be expected in the future for the other heavy metals. Sulfur is increasingly produced from desulfurisation of flue gases from refineries, power plants and other similar facilities. In Europe, there is no longer primary production of sulfur (Gielen 1997). Thus, it should be clear that only changes in demand for zinc can be determining for the primary zinc extraction.

Example:
The joint production of chlorine and sodium hydroxide is one of the classical examples of allocation problems. The chloralkali process yields three co-products:

$2NaCl + 2H_2O \Leftrightarrow 2NaOH + Cl_2 + H_2$

Hydrogen is produced in relatively small quantities (27 g for every kg of chlorine) providing approximately 3% of the world market for hydrogen. The main production route for hydrogen is steam reforming of natural gas and this will probably also be the preferred process to meet an increase in demand for hydrogen. As hydrogen does not fulfil the first condition, it cannot be the determining co-product. In addition, it can be noted that the value of the hydrogen is approximately 5% of the total income for the chloralkali process, which means that is does not fulfil the last condition either.

In practice, the chloralkali process is the exclusive production route for chlorine, which cannot be easily stored and is typically sold locally. Sodium hydroxide is a more flexible product that can be stored and transported over long distances. Sodium hydroxide can be substituted by soda ash directly or by sodium hydroxide produced by caustification of soda ash, thus providing both a floor and a ceiling on the price of this co-product (van Santen 1998a). Chlorine and sodium hydroxide are produced in approximately equal quantities by the chloralkali process and their share in the total income for the process is approximately the same. However, during the last 10 years there has only been one short period in 1990/1991 where the price of sodium hydroxide was so high that it could by itself provide adequate revenue to change the production volume (Beal 1995).

Based on this analysis of the market situation, it is concluded that long-term decisions on capacity adjustments are based on the existence of local, stable demands for chlorine, making chlorine the determining co-product for the chloralkali process when applied in LCAs with a long time horizon.

However, for some studies with a short time horizon, it may be relevant to regard sodium hydroxide as the determining co-product for the utilisation of the existing chloralkali capacity, in periods when the demand/price of sodium hydroxide is high. However, this situation is not likely to persist for longer periods, because of the existence of alternative production routes and substitutes for sodium hydroxide.

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 market will be cleared. In this situation, a change in demand for one of the joint products will influence the production volume of the joint production in proportion to its share in the gross margin of the joint production. This is equivalent to the result of an economic allocation. However, the resulting change in output of the other joint products influences their further downstream lifecycles, including their consumption and disposal phases, and thus requires the inclusion of the processes affected. This latter aspect of system expansion is ignored in a pure economic allocation of the joint production (see also section 5.10).

Example:
In pork production, the slaughtered pig is the basis for a large number of co-products. Independent variation among co-products is limited, although some flexibility exists, notably in the share of minced meat. All co-products must therefore be regarded as joint, and with some minor exceptions no alternative production routes exist. Thus, the pork market is governed solely by the output from the abattoirs and all prices are continuously adjusted so that all products are sold. Market trends are therefore aligned so that all joint products are simultaneously determining for the production volume. A change in demand for one specific part of the pig, e.g. tenderloin, will therefore influence the volume of production in proportion to the gross margin obtained for this part, relative to the average gross margin, equivalent to the result of an economic allocation. Since there are no alternative production routes, this change in production volume in turn affects the output, pricing and consequent consumption of all other parts of the pig.

The above theoretical illustration with the 4 joint products A,B,C, and D, also shows 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 demand.

It should be obvious that the two conditions above, and thus 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. When in doubt, or when conditions vary within the studied scale or geographical or temporal horizon, two or more alternative scenarios should be modelled.

5.5 Treating intermediate processes

The intermediate processes are those processes that take place between the split-off point where a dependent co-product leaves the processing route of the determining co-product and the point of displacement where the dependent co-product can displace another product (see also figure 5.2). 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.

The determining co-product for the intermediate processes is identified by investigating whether the condition of rule no. 2 (section 5.2) is fulfilled or not, i.e. whether the dependent co-product is utilised fully in other processes.

If the condition is fulfilled, the volume of intermediate treatment (and the amount of product being displaced) depends on the product volume of dependent co-product. Since the co-products cannot be independently varied, this volume is fixed by the determining product of the co-producing process. A change in demand for the dependent co-product will not lead to any change in the intermediate treatment (exactly because it is not determining, i.e. it cannot affect the volume of the co-producing process). Thus, the intermediate treatment and the co-producing process have the same determining product, and (as stated by rule no. 2) the intermediate process shall be fully ascribed to this product.

Example:
Cement may contain up to 40% of fly ash (a co-product from combustion processes), thus replacing the energy intensive raw material clinker. In most countries, all fly ash produced is fully utilised because of the obvious energy advantage. In this situation, the amount of fly ash used depends on the supply, i.e. on the volume of the combustion process producing the fly ash. Thus, this combustion process is ascribed the intermediate treatment (drying and transport) while being credited for the displaced clinker production.

Since in this situation, where the dependent co-product is fully utilised, it is the determining product for the co-producing process that also determines the amount of product being displaced, this product shall also be ascribed other possible changes resulting from the displacement. This applies to the changes in the alternative raw material supply, as in the example above, where the determining product for the co-producing process is ascribed (credited for) the changes in the displaced process, but also to such changes in the further life cycle of the dependent co-product that are a consequence of differences between the dependent co-products and the products they displace.

Example:
Compared to the displaced product, the dependent co-product may be of a different (typically lower) quality than the displaced product. This is often of no importance to the user (else the substitution would not have been accepted) but sometimes it may lead to an additional need for maintenance or other supplementary activities. These additional activities shall be ascribed to the determining product for the co-producing process.

Example:
Compared to the displaced raw material, the dependent co-product may contain a contamination, e.g. of heavy metals, which gives it a different performance during the final waste treatment of the product in which the dependent co-product is used. The difference in waste treatment and/or in environmental exchanges form the waste treatment shall be ascribed to the determining product for the co-producing process.

If, in the described situation where the dependent co-product is fully utilised, no point of displacement can be found, i.e. if the dependent co-product cannot immediately displace another product, the entire life cycle of the product in which the dependent co-product is used can be regarded as belonging to the intermediate treatment. Alternatively, it can be regarded as an alternative (but not necessarily more environmentally benign) waste treatment for the co-producing process. Both of these perspectives implies that the volume of the product in which the dependent co-product is used depends on the supply from the co-producing process, and that all processes in the life cycles for both the determining and the dependent co-products are to be ascribed to the determining product for the co-producing process. As the dependent co-product has a function (else it would be a waste) the resulting product system is strictly speaking still a system with more than one function. In spite of this, it is comparable to other product systems that solely yield the determining product. These other product systems shall not be expanded with the additional function (the one yielded by the dependent co-product) since this function is solely caused by the existence of the dependent product and not by any external demand[19].

Example:
Some discarded materials or worn-out products may be sold on a secondary market or reprocessed to fulfil some kind of leisure or luxury function, not necessarily replacing any other products, but simply implying an extra consumption. The reprocessing and use of these co-products shall be ascribed to the product system in which they originate. It should be noted that the price obtained for the (reprocessed) co-products will be taken from a consumer budget and can therefore not be used for other purchases. This may be regarded as a displacement of the marginal consumer spending, for which rules no. 2 or 3 (section 5.2) would apply.

If the condition of full utilisation is not fulfilled, it means that part of the dependent co-product is treated as a waste. In this situation, the volume of the intermediate treatment (and the displacement of waste treatment) is determined by how much is utilised in the receiving system, and not by how much is produced in the co-producing process. Thus, the product in which the dependent co-product is used, is determining the volume of the intermediate processes and shall be ascribed these (while being credited for the avoided waste treatment), as stated by rule no. 3 (section 5.2).

Example:
Use of the co-product fly ash as additive to cement is limited by a lack of standards for blended cements in countries with a relatively low amount of fly ash production (like Ireland and in Latin America). Also traditions and building codes for strength testing may limit the market for blended cements. In these situations, part of the fly ash may be deposited. Thus, a change in demand for blended cements may lead to more fly ash being used, and a displacement of the waste depositing. Thus, the blended cements should be ascribed the intermediate treatment and credited for the displaced waste treatment.

Example:
In the joint production of zinc and heavy metals, some primary cadmium is currently deposited and the same situation can be expected in the future for the other co-products from zinc extraction: mercury, lead, and sulfur. Thus, in this situation the product using these co-products should be ascribed the intermediate treatment, while being credited for the displaced waste treatment.

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[19] In the early version of the described procedure (Weidema 2001a), this situation was described by a special fourth rule, in addition to the three rules in section 5.2, while it is now seen simply as a special case of the second point in rule 2, namely that the intermediate treatment shall be ascribed to product A (the determining product for the co-producing process).

As illustrated by the examples, whether a co-product is utilised fully and whether it displaces other products, depend on market conditions that may change:

- over time,
- depending on location, and
- depending on the scale of change.

Thus, it is important always to note the conditions under which the determinant for the intermediate processes has been identified.

If the investigated change is of such a size that it in itself changes the conditions for the system expansion, i.e. changes which product is determining or whether the dependent co-product is utilised fully, the system expansion shall be calculated on the basis of the resulting conditions ***after*** the change.

The information needed to determine whether a dependent co-product is fully utilised are obtained from market and waste statistics and market studies, often available in-house in the involved industries. If it is uncertain whether this condition is fulfilled, it may be necessary to apply different scenarios to reflect the limited knowledge.

5.6 Waste or co-product?

In previously presented allocation procedures, it was important to distinguish between wastes and co-products, because the exchanges of the co-producing process should be allocated over the co-products, but not over the wastes and emissions. Waste is often defined in vague terms as 'outputs that need further treatment' (see e.g., Frischknecht 1994) or 'outputs that the holder discards or intends to or is required to discard' (EEC 1991) supported by exemplary or authoritative listings (e.g., the European Waste Catalogue 1994). In a more stringent way, waste can be defined as economic inputs and outputs (as opposed to inputs and outputs from and to the environment) with a value equal to or lower than zero (see e.g., Huppes 1994).

In the procedure presented here, the distinction between wastes and co-products is not important. If in doubt whether an output is a waste or a co-product, the output can be regarded as a dependent co-product and passed through the procedure. It will then fall under either rule 2 (the treatment of wastes that do not displace any other products would then be classified as an intermediate treatment and ascribed to the determining product for the co-producing process, just as a waste treatment would normally) or rule 3 (for "near-to-wastes" that are not fully utilised) of section 5.2. If a waste in the economic sense, i.e. an output without economic value to the process that produces it, displaces another product, the "waste treatment" is in fact a recycling, and rules 2 or 3 should therefore be applied in order to model correctly the consequences of this "waste treatment".

Thus, from the procedure presented here, a novel definition of waste may therefore be derived: ***A waste is a dependent output that does not displace any other product.*** This definition is in line with the intention of the definition in the European Waste Directive (EEC 1991) but gives a more precise distinction.

5.7 Recycling

Recycling has been regarded as presenting distinct allocation problems needing a separate treatment (for a number of articles on this topic, see Huppes & Schneider 1994). Examples of specific allocation procedures developed to handle recycling situations are the 50/50 rule (Ekvall 1994) and the material grade model (Wenzel 1998, Werner & Richter 2000).

However, the procedure presented earlier in this chapter is applicable for recycling, as for any other situation in which the same processes are shared by several products.

In the recycling situation, it is not difficult to identify the determining process for the primary life cycle. This is obviously the product of this life cycle, not the scrap.

The central issue is what determines the recycling rate and thus the degree to which the scrap is utilised in the secondary life cycle.

In an expanding market for the scrap product, such as is the case for most metals, all scrap collected will be used. In this situation, a change in the volume of the ***primary*** life cycle will lead to a change in the amount of scrap available for collection, and a change in the amount collected, and a change in the amount of scrap utilised in secondary life cycles, and thus in the displacement of “virgin” production (i.e. following rule 2 of section 5.2). A change in the volume of the ***secondary*** life cycle will not be able to influence the amount of scrap utilised, because it is already utilised fully. Thus, the change in the volume of the secondary life cycle must be covered by a change in “virgin” production (i.e. still following rule 2). However, it should be noted that a change in demand for scrap products may have indirect effects in the form of political intervention, reinforcing the signal sent by the change in demand, as also described in section 4.3. Such indirect effects are possible when significant quantities of scrap are available for collection, in addition to the amount already collected, and the costs of the additional collection is comparable to the costs of extracting “virgin” material. Such indirect effects should be described in separate scenarios, since they depend on political decisions that are difficult to predict.

In immature markets, the recycling might be below the economic optimum due to capacity constraints. In this situation, neither using nor supplying scrap will affect the recycling rate. An increase in demand will thus affect “virgin” supply, while an increase in supply to recycling will increase waste deposits. Only a specific action to remove the capacity constraints on recycling will effectively increase recycling. Also in this situation, a specific demand for scrap products may have long-term indirect effects that may be modelled in separate scenarios, as noted in the previous paragraph.

In a shrinking market, as we see for cadmium and some other heavy metals, some of the available material is being deposited, because there is not an adequate demand. A change in volume of the primary life cycle will only lead to a change in the amount of material to be deposited, whereas a change in the volume of the secondary life cycle will lead to a change in the amount being recycled, and thus indirectly also to a change in the amount being deposited (i.e. following rule 3 of section 5.2). It is interesting to note that in the case of cadmium (and possibly other heavy metals) the amount of recycling is fixed by environmental regulation, which means that it is “virgin” cadmium (as a by-product from zinc production) that is deposited, whereas in other situations it can be expected that it is the scrap material that would not be collected.

It may be argued that the studied changes in either the primary or secondary life cycle may also have a secondary effect on the market prices, and that this would equally affect the price of the primary product and of the collected scrap. This was the background for the so-called 50/50-rule suggested by Ekvall (1994) under the assumption that the supply elasticities of the “virgin” production and scrap were equal (i.e. that they would react to a price change with the same change in volume). Actually, the price elasticities are not equal (Ekvall 1999), and at the high recycling rates that exist in free markets with low entry costs (where the value of scrap is determined by the marginal cost of “virgin” production), the resulting volume change in collection is likely to be much less (probably often negligible) compared to the change in “virgin” production. This would support the above conclusion of applying rule 2 in the situation of expanding markets. Also in the case of a moderately shrinking market, where the supply from “virgin” production still plays a role, the difference in supply elasticities would imply that the “virgin” production will be affected most. However, in a rapidly shrinking market, the scrap can cover the entire demand and virgin supply would not be relevant. In this situation, a small change in volume of the secondary life cycle would only be able to affect the scrap collection, which is in line with our above conclusion of applying rule 3 in case of shrinking markets.

One of the reasons that recycling has been thought to demand a separate allocation procedure has been that - when the recycling rate is below its environmental optimum - both the user of scrap materials and the supplier of scrap may need an incentive to increase recycling, and that it is therefore important that the environmental advantage of increased use of recycled materials is distributed over the actors in the way that actually stimulates an increase the recycling rate. Furthermore, as the same material may be used over and over again in several consecutive life cycles, it has been seen as “unfair” if only the first or the last life cycle should carry the burdens of extraction and waste treatment.

The procedure presented here provides a clear cut-off between the individual life cycles, determined by whether there is an inflow of “virgin” material or not. In an expanding market, ***all*** life cycles affect the amount of “virgin” material extraction, and only the production that ensures an increase in the collection (by providing more material for recycling, or by specifically increasing recycling capacity, either technically, by economic support in parallel to the option of cross-subsidising suggested in section 4.3, or by stimulating political intervention) will be credited for the resulting increase in recycling (displacement of “virgin” extraction and decrease in waste handling). In a decreasing market without “virgin” inflow, ***all*** life cycles that utilise scrap products will be credited for the resulting increase in recycling (decrease in waste handling), and ***no*** life cycle will be credited for supplying additional material to recycling (since this would just mean that an equivalent amount would require waste treatment elsewhere). In this way, the procedure does not provide support for general incentives for using or supplying scrap, but provides an incentive for ***using*** scrap when the market for the material in question is decreasing, and for ***supplying*** scrap when the market is expanding, which is exactly what is needed to increase recycling in these two respective situations. When the recycling rate is below its environmental optimum, the procedure furthermore gives credit for ***specific*** actions that increase recycling capacity.

In some situations, the recycled material cannot displace "virgin" material, either because its technical properties have been reduced (e.g., paper fibres that become shorter for each recycling, so that after approximately six cycles they are so short that they must be discarded), or because it has been contaminated (e.g. copper in iron scrap, and silicon alloys of aluminium that cannot be recycled with the ordinary aluminium scrap). In these cases, sometimes described as downcycling, several distinct markets may exist for different qualities of recycled material, and the displacements that will occur will be determined by the supply and demand on these markets. If a demand for a specific scrap quality is not satisfied completely, scrap of higher quality or virgin material may be used, while scrap of lower quality cannot be used. When upstream processes deliver more scrap than the capacity of its downstream markets, some of the scrap will not be used. Thus:

1. A change in ***demand*** for a specific scrap quality will affect the next upstream, unused supply and will displace waste there. If all upstream supplies are used fully, it will affect "virgin" production.
2. A change in ***supply*** of a specific scrap quality will affect the next downstream, unsatisfied demand. If no downstream markets have unsatisfied demands, the scrap produced will not be used, thus affecting the immediate waste treatment.

A change in demand for a specific product, produced with scrap material, will cause both of the above.

In the case of contamination of virgin material, it should be noted that it is not only the current market situation that must be considered, but rather a very long-term market situation. As long as the current demand for scrap qualities is larger than the supply, all the contaminated scrap will be used and will displace "virgin" material. The contamination will be diluted due to the constant inflow of virgin material. However, at some stage in the future the scrap markets may become saturated, so that the contamination becomes a limitation for the recycling (this is already happening with copper contamination in iron scrap). The current contamination may thus lead to a future need for waste treatment of the contaminated material, or at least to a different displacement than on the current market (see e.g. Kakudate et al. 2000, Holmberg et al. 2001). It is this future market situation that should be used to determine what processes to include in the system expansion, since the immediate displacement of "virgin" material is only a temporary postponement of the necessary supply of "virgin" material in the future situation, when the contaminated material can no longer be used. The need to take into account these future effects is included in the third sentence of rule no. 2 of Box 3: "If there are differences between a dependent co-product and the product it displaces, and if these differences cause any changes in the further life cycles in which the co-product is used, these changes shall likewise be ascribed to product A."

For materials where the technical properties are reduced on recycling, each additional life cycle will imply a change in the quality of the material in the recycling pools, influencing the requirements for supplies of "virgin" material to the pools. The need for new material may be caused e.g. by degradation of fibres or polymers, as can be seen with paper or plastics. Thereby, the change in material quality may also be expressed as a change in the ability of the material to displace “virgin” material. A life cycle that delivers as much material to recycling as it receives will cause a change in material quality equivalent to the amount of “virgin” material supply that is needed to compensate for the reduction in technical properties. When less material is sent to recycling than what is received (i.e. when material is sent to waste treatment), the change in requirements for supplies of “virgin” material to the recycling pool (the change in displacement ability) will depend on the actual quality of the material that is thereby leaving the recycling systems. The quality (the ability to displace “virgin” material) can be estimated specifically by the physical properties or be calculated theoretically from the average recycling rate in the specific recycling pool, since the material quality will be reverse proportional to the recycling rate (with a low recycling rate the supplies of “virgin” material will be relatively large, which gives a relatively high material quality in the recycling pool – and opposite with a high recycling rate).

The EDIP’97-method (Wenzel et al. 1997) applies a factor, called the grade loss, to express the loss of grade or material quality on recycling. This grade loss is used as an allocation factor, in that every life cycle using the material is burdened with this fraction of the primary material production. The grade loss is calculated as the percentage of virgin material that must be introduced on recycling. Therefore, in terms of system expansion, the grade loss is equivalent to the difference between the amount used in a lifecycle and the amount displaced by the recycling from this life cycle, expressed in percentage of the amount used, i.e. the change in displacement ability as explained in the previous paragraph. Thus, given the same information on displacement, the EDIP´97-procedure will lead to the same result as the procedure presented here. Note, however, that he EDIP’97-method does not take into account the situation where the recycling pools are not utilised fully, which implies e.g. that in EDIP’97 the recycling process is always ascribed to the preceding life cycle.

Example:
In paper recycling, it may be assumed that paper fibres can only be used on average 6 times since the fibres become shorter and eventually must be discarded, so that each life cycle will imply an average loss of 17% of the “virgin” material. In EDIP’97-terminology this is expressed by a grade loss for paper of 0.17 per use, which means that a life cycle that receives 1 ton of recycled paper and after use sends 1 ton to recycling should be ascribed 17% of the exchanges from the primary production of 1 ton of paper and 17% of the exchanges from disposal of 1 ton of discarded fibres. In the terminology of system expansion, the life cycle that receives 1 ton of recycled paper (under the condition of full utilisation of the specific recycling pool and that “virgin” paper is displaced in the proportion 1 to 1) shall be ascribed a consumption of 1 ton of “virgin” paper, and – when 1 ton is sent to recycling after use – be ascribed the waste treatment from this (the scrapping of 170 kg discarded fibres) and be credited for the displacement ability of this after one life cycle (830 kg primary production; again under the condition of full utilisation of the recycling pool). The result is that this life cycle is ascribed 170 kg primary production and 170 kg waste treatment, exactly equivalent to the 17% of the used amount of 1 ton prescribed by the EDIP’97-method. When less material is sent to recycling than what is received, or when the receiving market is saturated, less “virgin” material is displaced, depending on the material quality in the lost material, for example the displacement ability of recycled newsprint in Denmark in 1995 could be estimated to be 50% (based on a realised recycling rate of 65%) and for corrugated board with a recycling rate of 75% the displacement ability will be approximately 32% (meaning that for each time 1 ton of corrugated board is sent to waste treatment, the

requirement for “virgin” material in the recycling pool is increased with 320 kg). The displacement ability is directly corresponding to the concept of “residual material grade of scrap” in the EDIP’97-method.

5.8 Services as co-products

The situation where the co-products are services (e.g., waste treatment or transport) has also been regarded as presenting distinct allocation problems, also known as ***multi-input allocation*** because the co-products are typically related to physical inputs to the process (e.g., the waste to be treated, or the goods to be transported).

In the procedure presented here, the same method is used for service products as for material products (goods). The typical examples used are combined transport and combined waste treatment. It appears that most service outputs supplied to multiple product systems can be independently varied, and therefore treated already by step 1 of the procedure (see figure 5.3). However, we have been able to find at least one example of a joint waste treatment service that requires the use of system expansion (joint neutralisation of waste acids and bases):

Example:
The neutralisation of waste liquids with extreme pH-values can be done by proportional mixing, where one waste neutralises the other. The waste-based neutralisation process thus supplies two services: Waste-based acid neutralisation and waste-based alkali neutralisation. If the two wastes are not available in the right proportions, the amount of waste-based neutralisation is determined by the least available waste. If there is more alkali than acid waste available, the remaining alkali waste must be neutralised by “virgin” acid. In this situation, an additional demand for acid neutralisation (the determining product) will lead to additional waste-based alkali neutralisation, displacing alkali neutralisation by “virgin” acid. An additional demand for alkali neutralisation (the non-determining product) must be satisfied by neutralisation by “virgin” acid (since all waste acid has already been used).

Secondary functions of forestry and agriculture, such as maintaining rural income and maintenance of landscapes for recreation, may also be used as examples of service co-products that can be treated by the procedure in complete parallel to physical products. As the name implies, these functions are typically secondary compared to the production of physical products. Thus, the secondary functions may be regarded as non-determining co-products, while the physical product (e.g. wheat or wood) is typically the determining product. The demand for the physical product can change either as a result of changes in the market or changes in crop specific subsidies. In both cases, the fulfilment of the secondary functions is affected (e.g. causing changes in rural income or landscape maintenance compared to the desired output of these functions). This change may or may not be counteracted by alternative measures, but can in both situations be covered by rule no. 2 of section 5.2. The affected alternative measure (i.e. the most sensitive measure for supporting rural income or for landscape maintenance, respectively) depends on the current policies in the specific situation. In some situations, the so-called secondary functions may in fact be the primary concern, e.g. when rural income support is administered per land area or when landscape maintenance is rewarded without requirements to what crops should be grown. If this source of income leads to changes in the production, the subsequent change in composition of product output may be one of the side-effects that has to be accounted for by including the alternative production displaced. This may involve a number of subsequent changes on different markets.

5.9 Complex situations

The situation described by figure 5.1 is a simplification, in that it shows only one determining and one dependent co-product (i.e. only two products coming out of process A) and none of the other processes have co-products. Therefore, this section deals with the more complex situations:

- where process A has more than two co-products,
- where multiple products result from the intermediate process or where the dependent co-products have other applications than in process B, and
- where the displaced process has multiple products.

More than two co-products seems to be rather the rule than the exception when processes have more than one product, as can be seen from most of the examples in the previous sections. This, however, poses no problem for the procedure. Each co-product can be treated separately:

- when studying a change in output of a determining co-product, and there are more than one dependent co-product, the consequences for each of the dependent co-products can be analysed in isolation, one at a time,
- when studying a change in output of a determining co-product, and there are more than one determining co-product, the changes in the co-producing process can be analysed in isolation, separately from the analysis of any dependent co-products,
- when studying a change in output of a dependent co-product, the only thing to be investigated is whether the dependent co-product is utilised fully or not, which can be done without concern for any of the other co-products.

Multiple products resulting from an intermediate process (i.e. a process occurring after the split-off point and before displacing other products) means that the dependent co-product is split up in two or more fractions, each following its own route. Each fraction may be fully utilised in other processes (rule no. 2 of section 5.2) or only partly (rule no. 3). Each fraction can be treated separately, although fractions that follow the same rule may be treated together for convenience (listing the affected products and processes together). Even when the co-product is not composed of separable fractions, it may have many different applications. Then, the process to be considered in the system expansion is the application most sensitive to a change in supply (as identified by the procedure in chapter 4).

Displaced processes that have multiple products, of which the displaced product is only one, will require a repetition of the procedure for each of the co-products from the displaced process. If this leads again to another process with multiple products, as illustrated in figure 5.4, one might fear that this system expansion would continue without end. However, the number of possible processes involved in the system expansion is limited by the very procedure, since:

- the number of markets affected by each displaced process is limited, and the displaced process is only that specific supplier to each market, which is most sensitive to a change,
- the three rules for system expansion (section 5.2) provides clear cut-offs between the different product systems involved (either a process is included or excluded from the studied system),
- for each time the system expansion is iterated, both the economic value and the volume of the displaced processes tend to decrease, because in each iteration the avoided 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.

Example:
In Europe, the co-production of chlorine and sodium hydroxide involves a displaced production of sodium hydroxide (see also example in section 5.4), which can be identified as the combination of the Solvay process: $2NaCl + CaCO_3 \Leftrightarrow Na_2CO_3 + CaCl_2$ and the lime-soda process (caustification): $Na_2CO_3 + Ca(OH)_2 \Leftrightarrow 2NaOH + CaCO_3$ with recycling of the calcium carbonate, giving net process: $2NaCl + Ca(OH)_2 \Leftrightarrow 2NaOH + CaCl_2$. Caustification is not a commercial process, but it is used by industry (Kirk-Othmar 1978, van Santen 1998a). Thus, this displaced production route has a co-product, calcium chloride, which can be used for de-icing and dust control because of its hygroscopic properties. However, it is not a very valuable product and part of it is deposited (Moody 1969, Gerhartz 1985). Thus, following rule no. 3, the displacement of the alternative production route for sodium hydroxide will lead to a reduction in calcium chloride deposition. In summary, chlorine will be ascribed the displacement of the alternative production route for sodium hydroxide and credited for the reduced calcium chloride deposition. Using the nomenclature of figure 5.4, the cut-off is after process D and W_2, since there is no displacement of alternative supplies to process C (de-icing and dust control with calcium chloride), i.e. process E does not exist, since there is adequate unused supplies in W_2.

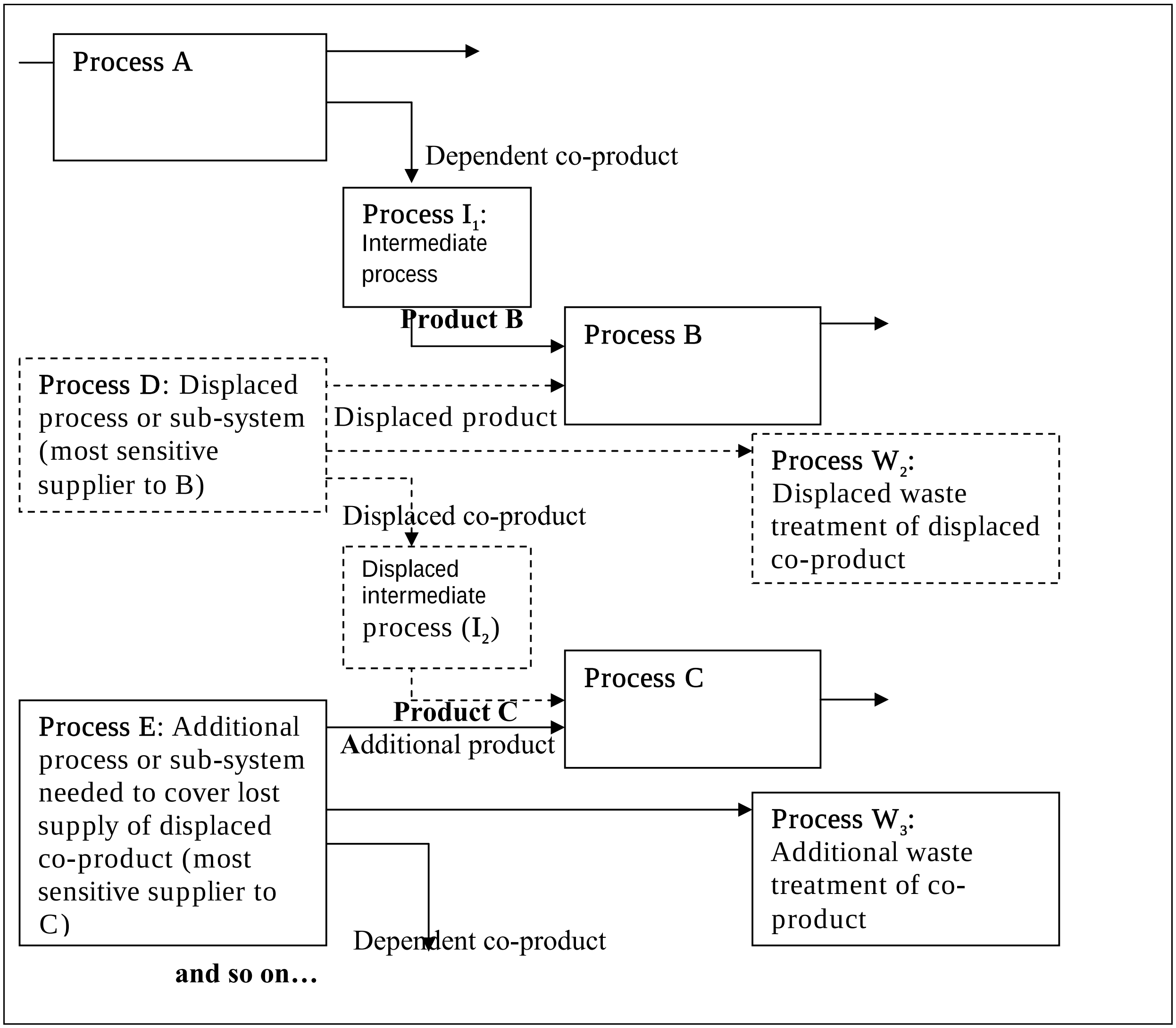
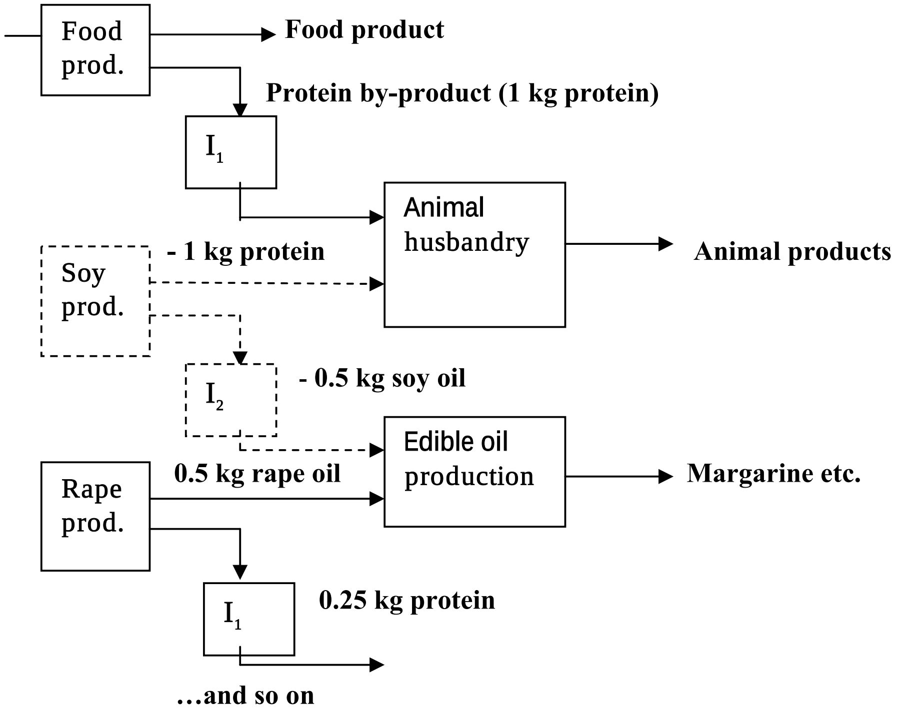


Figure 5.4 System expansion and delimitation when the displaced process has multiple outputs

In Weidema (2003) an example is provided of an iterative solution of the joint production of ethylene and propylene from steam-cracking, where an additional output of ethylene yields also an output of propylene, the displaced production of which again leads to a by-product of ethylene and so on. Below, a similar example with joint production of protein and vegetable oil is given. This example was first published in Weidema (1999).

Example:

Protein by-products from the food industry displace the most sensitive protein source, which is soy meal (see section 4.8). Besides protein, soy production yields the co-product soy oil. The displaced soy oil production will thus lead to an increase in the most sensitive alternative supply of edible oil, which is rapeseed oil (see section 4.8). This gives then an additional amount of rape seed protein as a co-product, which then again displaces more soy protein and so on. Since only two global markets are involved (the fodder protein market and the edible oil market), this loop can easily be closed. The calculation is based on the relative content of oil and protein in the two products. Since soy beans yields half as much oil as protein, while rape yields just the opposite ratio, it can easily be seen that for every amount of soy protein displaced, half the amount of oil is displaced, leading to the displacement of again half of this amount of protein, i.e. 25% of the original amount of protein.



By iteration, it can be calculated that 1 kg of raw protein in a food industry by-product requires the following system expansion:
a reduction in volume of soy protein of $1 + 0.25 + 0.25^2 + 0.25^3 + ... = 1.33$ kg raw protein, which is equivalent to 3.9 kg soy beans (at a protein content of 34%), and
an increase in rape production of $0.25 + 0.25^2 + 0.25^3 + ... = 0.33$ kg raw protein, which is equivalent to 1.66 kg rapeseed (at a protein content of 20%).

This may also be expressed as the solution to a system of linear equations. If the products are named a and b, the suffixes A and B signify the originating processes, and the 1 represents the desired product output:

$\mathbf{a}_A + \mathbf{a}_B = 1$
$\mathbf{b}_A + \mathbf{b}_B = 0$
this system may be solved by iteration or by Gauss-Jordan elimination when expressed in matrix form.

This is simply a specific case of the general solution for a life cycle inventory with the normalised output of 1 unit of **a**. While the system described above is limited to the product outputs from the co-producing and displaced processes, a standard product system include also the upstream and downstream processes and their product flows (product inputs to a downstream processes expressed as negative amounts in the downstream process).

Therefore, the solution can be generalised to any number of products **a, b, c,** etc. and any number of processes A, B C. etc. Below an example is provided with 5 interdependent fishery processes which all produce two or more of the 5 fish products.

Example:
Five fishery processes and their relative production of five fish products are shown in the below table.

Relative amounts of products	B:Cod-fishery	C:Plaice-fishery	D:Lobster-fishery	E: Pelagic fishery	F:Industrial fishery
b: cod	1.0000	0.1779	0.6657	0.0040	0.0007
c: plaice	0.0361	1.0000	0.2163	0.0000	0.0005
d: lobster	0.0041	0.0000	1.0000	0.0000	0.0000
e: herring and mackerel	0.1187	0.0000	0.0000	1.0000	0.0129
f: industrial fish	0.0299	0.0197	1.0478	0.3618	1.0000

The solutions are provided below for outputs of 1 unit of each of the five products (with all other product outputs neutralised to 0):

Resulting amounts of processes required for 1 additional unit output of:	B:Cod-fishery	C:Plaice-fishery	D:Lobster-fishery	E: Pelagic fishery	F:Industrial fishery
b: cod	1.0096	-0.0356	-0.0042	-0.1201	0.0183
c: plaice	-0.1796	1.0063	0.0007	0.0216	-0.0230
d: lobster	-0.6327	-0.1935	1.0026	0.0888	-1.0599
e: herring and mackerel	-0.0038	0.0003	~0.0000	1.0052	-0.3636
f: industrial fish	-0.0005	-0.0004	~0.0000	-0.0129	1.0047

This shows that any complexity of co-products can be handled simply by including the affected processes in the product system and using the standard procedure for solving the system (by either iteration or matrix reduction). The most difficult part is thus not the mathematical solution, but the identification of the affected processes and the acquisition of environmental data for these processes.

As part of the Dutch methodology project (Guinée et al. 2001), we had the opportunity to show how the procedure presented in this chapter compares to an economic allocation of the same relatively complex system, namely that of a (hypothetical, simplified) refinery, both receiving co-products (waste from other processes) and supplying a number of both joint and combined co-products. This example (first published in Guinée et al. 2001, part 2b, pp. 36-41 where our method was named “symmetrical substitution method”) is reproduced in annex A, while the economic allocation of the same refinery process can be found in Guinée (2001, part 2b, pp. 32-35).

5.10 Traditional co-product allocation as a special case of the presented procedure

In traditional co-product allocation, the exchanges of the co-producing process is partitioned and distributed over all the co-products according to a product specific allocation factor between 0 and 1, and there is no inclusion of intermediate and displaced processes.

Expressed in the terms of consequential LCA, this implies that for any co-product, the co-producing process is assumed to react to an increase in demand with an increase in production volume in proportion to the product specific allocation factor. For example, a demand of 1000 kg of a co-product with the allocation factor 0.1 will lead to an increase in production volume of the co-producing process resulting in an increase in output of 100 kg of the demanded co-product. This further implies that the remaining part of the demand (here 900 kg) is covered by an alternative supply and/or a reduction in consumption elsewhere, and that the environmental impacts of this are assumed negligible, since the system is not expanded to include this alternative supply and/or changed consumption and related processes.

In a joint production, the increased production volume of the co-producing process implies an equivalent increase in the output of the other joint products. In traditional co-product allocation, since the system is not expanded to include the further fate of these joint products (displacement of alternative supply, increase in consumption and/or waste handling), the implied assumption is that this further fate is having negligible environmental impacts.

This may lead to serious inconsistencies when the alternative supply, consumption or waste handling is included elsewhere in the same product system. For example, in a product recipe using both sunflower oil and soy beans, a traditional allocation of the sunflower production would allocate part of the sunflower production to the sunflower protein cake, but not include the soy production displaced by this additional supply of sunflower protein, while the same soy production would be included for the soy beans used directly in the recipe.

However, there may be situations in which the reaction of the co-producing process to an increase in demand for its co-products ***is*** proportional to specific allocation factors, and where at the same time neither alternative supply, consumption, nor waste handling of the co-products will be affected. This is the case when:

- several co-products are determining the volume of the co-producing process in different periods within the time horizon of the study, so that the exchanges of the co-producing process can be allocated over the co-products in relation to the relative lengths of these periods[20], and

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[20] This may also be expressed in terms of relative influence of the co-products on the production volume of the co-producing process, which may be represented by long-term price elasticities. As a further approximation, allocation factors based on revenue or gross margin (as in cost allocation) may be seen as proxies for price elasticities.

- the co-products can be stored (without additional environmental impact) during the periods that they are not determining, so that no additional intermediate treatment and no displacement occurs.

Thus, in such a situation, the traditional co-product allocation may be regarded as a special case of the procedure in figure 3.2.

As mentioned in section 5.4, several joint products may influence the production volume of a joint production in proportion to their share in the gross margin of the joint production, when the normalised market trend of all the joint products is aligned as a result of constraints in alternative production routes. In this situation, co-product allocation according to gross margin may correctly reflect the way the co-producing process will be affected. However, as there is no storage of co-products (exactly because the markets are cleared), intermediate treatment and consumption of the co-products will be affected, and the co-product allocation must be supplemented by a system expansion with the affected processes.

As a more academic question, it may be asked whether the entire procedure presented in this chapter could be called “co-product allocation,” rather than a way to ***avoid*** allocation. This basically depends on the original viewpoint. If the co-products and their further fate are originally regarded as being outside the studied system, it is reasonable to regard the presented procedure (in which the changes in the processes affected by the change in amount of co-products are added or subtracted from the studied system) as a way to avoid allocation. If the originally studied system is regarded as including the co-products (and their further fate, as well as the processes that the co-products may displace), the presented procedure can be regarded as an allocation of the different changes in production volumes over the different co-products. The word “ascribed” in the four rules can be replaced by “allocated”, and the procedure of “crediting” can be understood as “allocating the decrease in production volume to”. In that case, the term “system expansion” is a misnomer, and should preferably be named “market-based allocation”.

In the ISO standard 14041, system expansion is regarded as a way to avoid allocation, and we have therefore maintained this viewpoint in the present chapter. Step 1 in the procedure in figure 5.3 (dealing with combined production) is equivalent to step 2 in the ISO procedure (allocation according to physical relationships), but because the output of all other co-products are kept constant, these co-products may as well be regarded as being originally outside the studied system, meaning that there is no allocation problem. The entire presented procedure can therefore be regarded as “avoiding allocation.”

5.11 Relation to the procedure of ISO 14041

Because – as shown in this chapter – system expansion is always possible for cases of joint production in consequential LCA studies, the stepwise procedure of ISO 14041 (ISO 14041, clause 6.5.3) will lead to the same results as the procedure presented in figure 5.3:

- Step 1 in the ISO procedure requires that system expansion shall be performed wherever possible. As shown above, this applies to all cases of joint production in consequential studies.
- Step 2 in the ISO procedure requires that, when ISO step 1 cannot be applied, allocation shall be done “in a way which reflects the underlying physical relationships between them” (“them” being the co-products), i.e.

reflecting "the way inputs and outputs are changed by quantitative changes in the products." This is also known as allocation according to physical causalities (Guinée et al. 2001) and is equivalent to step 1 of the procedure in figure 5.3. This step is relevant for cases of combined production in consequential studies. The order of step 1 and 2 in the ISO procedure is not significant for the result of applying the procedure, see below.

- Step 3 in the ISO procedure provides the option to allocate according to the relative economic value of the co-products[21]. For consequential studies, all possible cases of co-production (combined and joint) were covered by ISO steps 1 and 2, which means that ISO step 3 is only relevant for attributional studies. It should be noted that ISO step 1 and 2 could also be applied to "hypothetical consequential" studies that analyse hypothetical, historical changes (see sections 1.2 and 5.1).

Since each step in the ISO procedure can be related to a specific group of cases (step 1: joint production in consequential studies; step 2: combined production in consequential studies; step 3: attributional studies) the step-wise nature of the ISO procedure is unnecessary. Simply describing the application area of each step in the procedure, as suggested here, would give a more straightforward presentation.

In the procedure presented in this article, step 1 deals with combined production (ISO step 2), while steps 2 to 4 deals with system expansion (ISO step 1), because it appears more logical to deal first with the simple case, where the outputs of the other co-products can be kept constant without system expansion, before dealing with the more complicated cases, where the outputs of the other co-products can only be kept constant by applying system expansion.

However, in practice the order does not matter. If applying system expansion to a case of combined production, the same result will be obtained as when applying the simpler procedure of step 1 of the procedure presented in this article. In fact, step 1 can be treated as a special case of the model for system expansion if the limiting parameter for the combined production is seen as the determining co-product, and the non-limiting parameters as the dependent co-products.

Example:
In a situation where combined transport is weight-limited, the determining co-product could be described as "transport of weight (mass)". The dependent co-product "transport of volume" is not utilised fully. An additional demand for transport of volume alone (i.e., provided it has no weight!) can be satisfied without changes in the co-producing process, that is, the co-producing process is fully ascribed to the determining co-product (rule no. 1). If the co-transport is substituting another transport (i.e., a separate transport of a light-weight product), it is the transport of this light-weight product that benefits from shifting to co-transport, because the unutilised volume in the co-transport would else have been wasted

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[21] The ISO text states "in a way which reflects other relationships between them" (i.e. between the co-products). The close parallel to the wording in step 2 of the ISO procedure reveals that it is still causalities that are intended as allocation factors. Thus, step 3 should not be seen as an opening for any arbitrary allocation key (Jerlang et al. 2001), as this would also render the standard meaningless on this point. In practice, economic causality is the only non-physical causality that has so far been suggested as allocation key.

(although not requiring any waste treatment!). This is a variation of the reasoning behind rule 3.

Step 2 of the ISO procedure may also be regarded as a special case of the very first procedural step of the ISO procedure, which we have ignored in the above presentation, namely the obvious option of avoiding allocation by subdividing the process into sub-processes that only produce one product. Such a subdivision is obviously not possible for joint production as is mainly relevant when “black box” data have been collected for a production that is in fact an aggregate of independent production lines. However, in consequential LCA, combined production may be regarded as such independent production lines, since it is possible to measure the independent reaction of the co-producing process to variation in output of each co-product separately.

When step 2 of the ISO procedure is regarded as describing special cases of either process subdivision or system expansion (both termed “avoiding allocation” in ISO 14041), it would be more relevant to include it in step 1, before the description of system expansion, i.e. resulting in the same order as in the procedure in figure 5.3.

Besides the three-step procedure, ISO 14041 (section 6.5.2) prescribes an allocation principle, which has popularly become known as “the 100% rule”: “The sum of the allocated inputs and outputs of a unit process shall equal the unallocated inputs and outputs of the unit process”, i.e. there should not be any exchanges that are allocated twice or not allocated at all. Although, according to the ISO text, this principle applies only to allocation and not to ***avoiding allocation***, it is worth noting that the procedure presented in this article adheres to this principle: The three rules in section 5.2 ensure that all processes are fully ascribed to (allocated to) either one or the other co-product.

6 Forecasting future processes

Forecasting is the activity of producing a forecast. A forecast is a statement about the future. Forecasting is done in almost all aspects of life and at a number of different levels. Weather forecasting, forecasting of sales curves and technology forecasting are commonly used.

In the previous chapters, reference was made to the time horizon of the studied change, and it was made clear that the processes to include in the studied product systems may change over time, depending on the future market situation. The topic of this chapter is the actual forecasting procedures to be applied.

The alternative to forecasting is the use of unjustified assumptions about the future or the use of data for the current situation as proxies for data for the future situation. While this may be adequate in some situations (and especially in the first iteration of a life cycle assessment) and for some parts of the product systems, the use of forecasting is often necessary to ensure adequate validity of the data used and the conclusions drawn. The purpose of this chapter is to show the relevance of forecasting and to recommend a procedure to improve the consistency and transparency of the forecasting.

Forecasting product systems includes both:

- The forecasting of the future market situations to be used in the procedures given in chapters 3 and 4, to allow the identification of the relevant processes to include in the product systems, i.e. forecasting of:
    - Obligatory product properties
    - Geographical and temporal market boundaries
    - Market ties between specific suppliers and customers
    - Market trends
    - Production constraints
    - Relative production costs etc., for each possible supplier/technology
- The forecasting of the technologies of the specific processes identified as relevant
- The forecasting of the exchanges of the specific processes identified as relevant

6.1 Procedure

The procedure consists of five steps (illustrated in the flowchart in figure 6.1):

1. Determining the parts of the product systems to be forecast
2. Determining the necessary detail of forecasting
3. Choosing the relevant forecasting methods
4. Forecasting
5. Consistency check

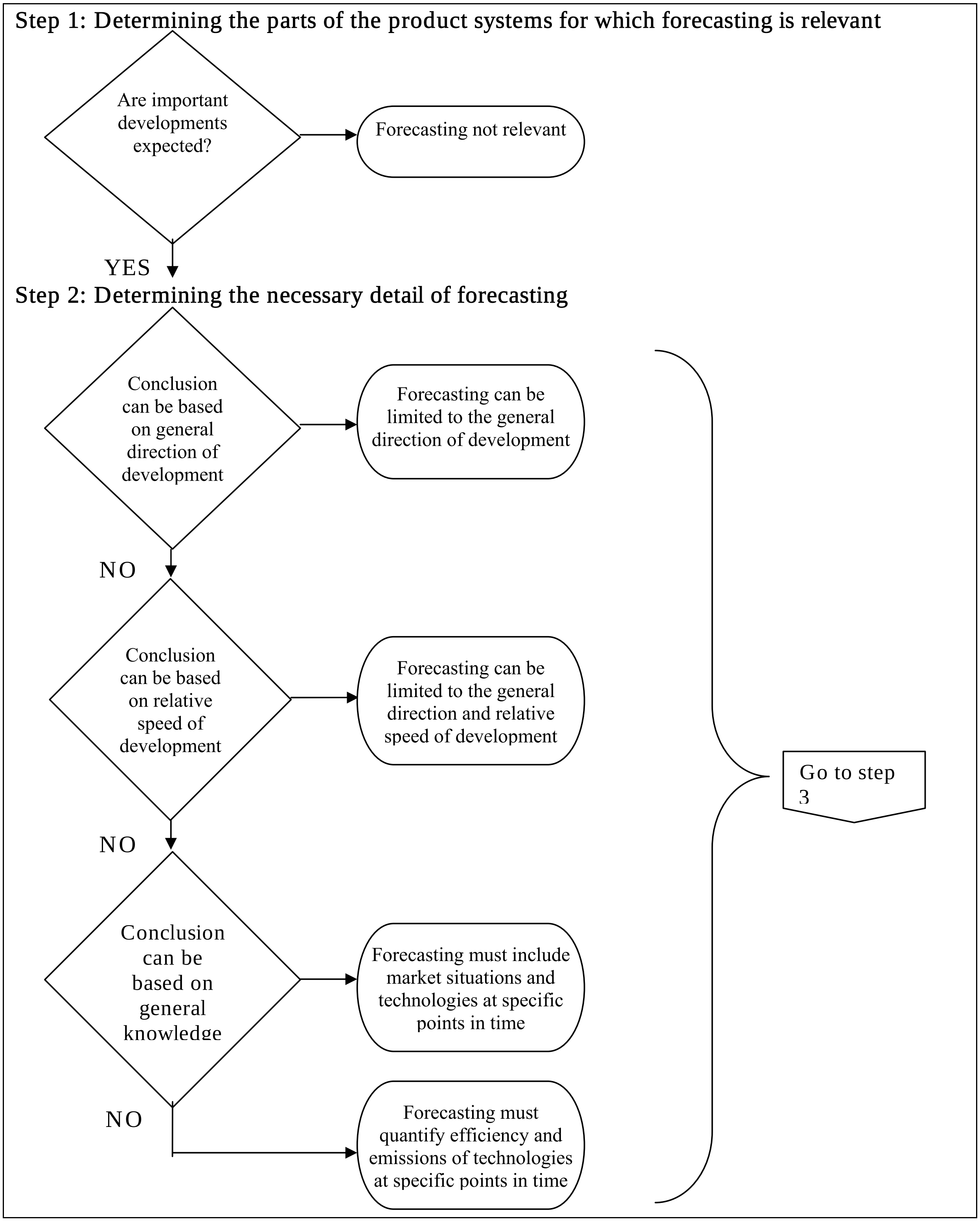
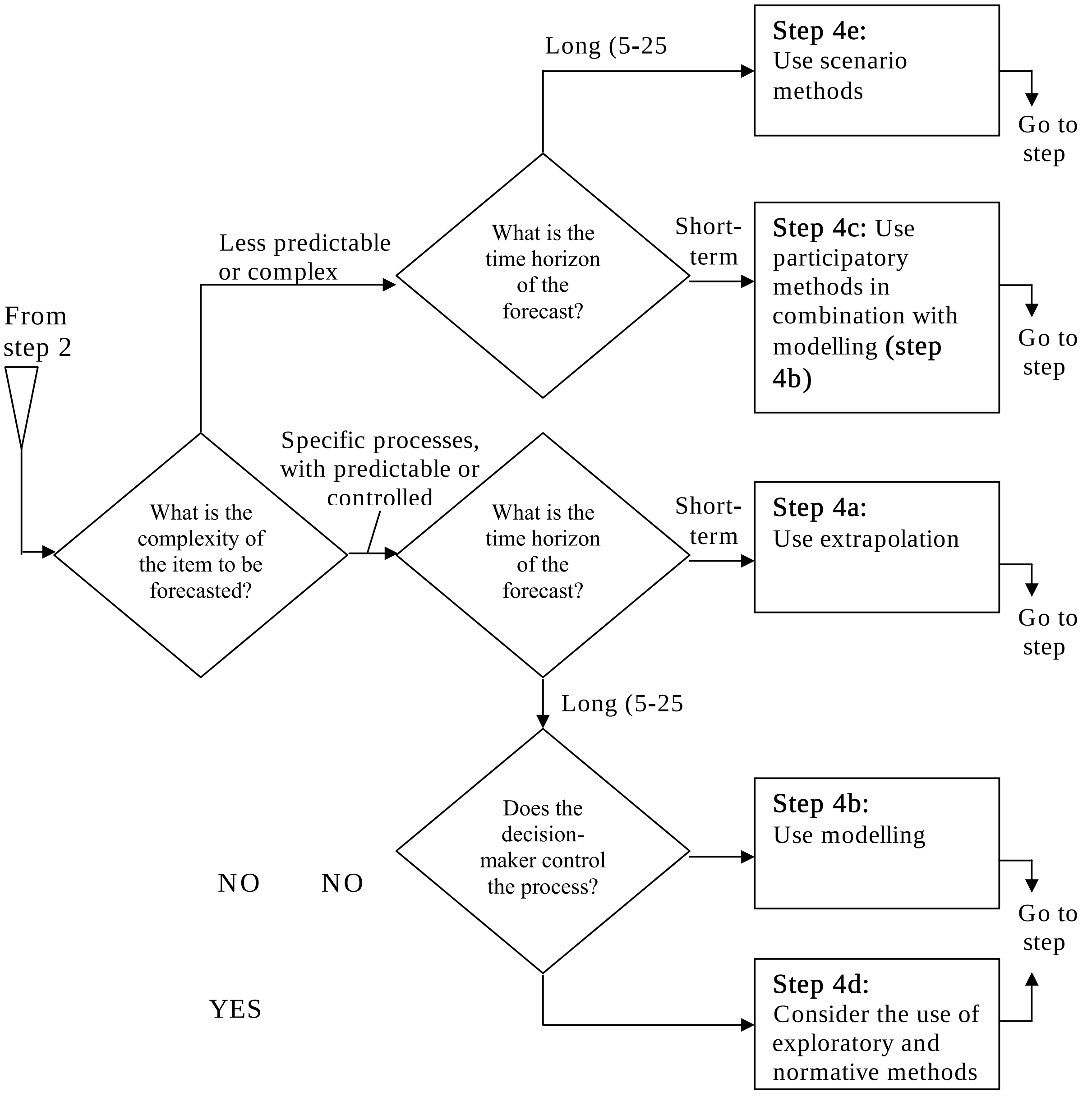


Figure 6.1(a). Decision tree showing the 5-step procedure for forecasting product systems. Figure continues on next page.

Step 3: Choosing the relevant forecasting method



6.1.1 Step 5: Consistency check

Figure 6.1(b). Decision tree showing the 5-step procedure for forecasting product systems. Figure continued from previous page.

6.2 Determining the parts of the product systems for which forecasting is relevant

It may not be equally important to forecast all parts of the product systems. There may even be entire life cycle assessments where forecasting is not necessary. The factors that need to be considered are:

- The general speed of development of the relevant markets, technologies and exchanges
- Expectations about radical or untypical developments
- The time horizon of the study relative to the expected development
- The position of the specific process in the life cycle of the product

Speed of development

Markets generally develop more slowly as they mature. With time, the product becomes more well-defined (the obligatory product properties tending to become more encompassing), and the market boundaries and production constraints less volatile (tending to be determined more by natural geography, such as climate and natural transport barriers, than by administrative differences). Likewise, the production costs and technologies develop more slowly as the ultimate physical constraints of each material, process or technology is approached. There have been several attempts at classifying different industrial sectors according to their speed of development, but none of them are fully satisfactory. An example is given in table 6.1. For a given technology, the size of most process exchanges will decrease over time, following the general efficiency development in the corresponding technology, but for exchanges that are in focus because of their economic value or their known environmental impacts, the speed of development may be above average (example: the phasing out of CFC's).

Table 6.1. Sectors that can be described as either fast or slow concerning technological changes. Years for adjustment of technologies, based on expenditure for research, development and licensing (from Barbiroli 1997). Note that several technologies can be used within one sector. This means that the speed of change can only be considered as an average.

Traditional sectors > 10 years	Mixed sectors 5-10 years	Advanced sectors 1-5 years
Building materials Foodstuff Inorganic chemicals Iron metallurgy Non-ferrous metals Paper Petroleum Railways Textiles, clothing, footwear Wood	Basic and intermediate chemicals Electrochemicals Machinery Motor vehicles Rubber	Aeronautics Artificial and synthetic fibres Electronics Frozen and freeze-dried foods Pharmaceutical Plastics

Radical or untypical developments

The general considerations in the preceding paragraph may be overruled by specific knowledge in specific situations. Even traditional sectors may be subject to sudden, radical changes determined by larger shifts in other sectors or in general technological developments or socio-economic conditions. For example, over the last decade development in the vehicle sector has been speeded up by pre-announced regulation on emissions. Another example is the introduction of genetic engineering, which may cause sudden, radical changes to the otherwise technologically mature food sector.

6.2.1 Time horizon of study

The general need for forecasting depends on the relation between the time horizon of the study and the general speed of development, taking into account also any untypical developments. The time horizon of the study is determined by the period for which the conclusions of the life cycle study should be valid plus the life-time of the affected capital investments. This period is typically considerably longer than the lifetime of the product. The period for which the conclusions should be valid is related to the application area of the study (cf. figure 1.1). Forecasting is typically relevant if the time horizon of the study is longer than 5 years. In addition, forecasting is relevant in sectors with rapid development or if radical or untypical developments can be expected.

6.2.2 Position in the life cycle

Even when the time horizon of the study is longer than 5 years, not all processes in the life cycle may be affected so far into the future that forecasting becomes relevant.

6.3 Determining the necessary detail of forecasting

As any other aspect of life cycle assessment, forecasting may be made in more or less detail. Covering the most important processes in the studied life cycles, a forecast may include (in order of increasing detail):

- the general ***direction of the development***, in terms of technology and exchanges,
- the ***relative speed of development*** of the relevant processes,
- the situation at ***specific points in time***, corresponding to the time horizon of the study,
- the ***specific technology and its exchanges*** at such specific points in time.

If the general direction of development confirms or enhances the current situation, this qualitative information may be adequate as an addition to a life cycle study based on current or historical data. For example, to conclude that an alternative energy source that is currently competitive versus fossil fuels will continue to be competitive, it is adequate to have the general knowledge that costs of fossil fuel resources will be slowly increasing on the long term (as reserves are depleted) and that costs of the alternative energy source will continue to fall (following an ordinary learning curve).

The relative speed of development of different processes must be taken into account if the direction of development does not in itself provide a clear indication, and if the speed of development is not uniform for all the involved processes. This information, which is still qualitative, may sometimes be adequate basis for a conclusion. For example, when the price of all fossil fuels are expected to increase in the long run, it is necessary to know the relative speed of price developments for coal, oil, and natural gas, in order to determine which fossil fuel will be the most competitive in the future.

Combining knowledge on the direction and speed of development with more quantitative information allows forecasts of the market situation and the technologies involved at specific points in time. For example, information on the current costs of coal and wind power and the actual speed of cost developments for these two technologies (e.g. expressed in average percentage change in raw material costs and efficiency per year and/or as a coefficient of a learning curve) will allow to forecast whether wind power or coal power is the most competitive at a specific point in time.

If necessary, the relevant technologies may then be further quantified, also in terms of exchanges, by combining specific technical information with general forecasts on technical efficiency and emission control.

An example of a forecast combining knowledge on the direction and speed of development can be found in Prognos (1999).

6.4 Choosing the relevant forecasting method

Several methods can be used for forecasting, some of which are more commonly used for specific applications. The most extensive description of methods is by the UN millennium project (Glenn 1994a, 1999). Other reviews of methodology are made by Bell (1997), Donnelly (1997), Vanston (1995), and Martino (1972).

The number of described methods varies between the different reviews. Also, terminology is variable and overlaps occur. Strict definitions of the specific methods are generally lacking.

The taxonomy suggested by the UN millennium project (Gordon 1994a, 1999) distinguish the methods as either:

- normative or exploratory, and
- quantitative or qualitative.

However, the authors describe themselves the shortcomings of this taxonomy: The normative/exploratory dimension relates more to the application of the methods than to the methods themselves. Many methods are used for both normative and exploratory forecasting. As for the quantitative/qualitative distinction, it is argued that even quantitative methods use qualitative assumptions and a qualitative method can use numbers (Glenn 1994b).

Other taxonomies have been suggested by Vanston (1995), dividing according to different views of the future (extrapolators, pattern analysts, goal analysts, counter punchers and intuitors), and Michael Marien (cited in Glenn 1994b) using a division according to 7 P's (probable, possible, preferable, present, past, panoramic and participatory).

We have found it most useful to divide the methods into 6 groups:
- Extrapolation,
- Modelling,
- Exploratory,
- Scenario,
- Participatory,
- Normative,

which we describe shortly below. The forecasting method to apply in a specific situation depends on the time horizon of the forecast and the predictability and complexity of the item to be forecast (see table 6.2). The choice of method does ***not*** depend on the required detail.

Extrapolation is based on extending historical and current trends into the future. It is based on a belief that the future represents a logical extension of the past and that information contained in historical data can be extracted, analysed, and reduced to one or more equations that can be used to predict future events. This may be adequate for short-to-medium term forecasts of specific processes, when no radical or untypical developments are expected. A forecast based on extrapolation may also be used as a surprise-free base-line forecast ("suppose things keep going as they have in the past ...") for the modifications of other methods. Trend analysis, time series, regression, econometrics, and simulation modelling belong in this group (Futures Group 1994a).

Modelling seeks to identify the determining mechanisms and to model how the combined effects of several mechanisms will influence the future. It is based on a belief that future events will be influenced by mechanisms analogous to those determining past events. Thus the best way to describe the future is by identifying the determining mechanisms and to model how these will influence the future. In this way, probabilities rather than possibilities are considered. Examples of methods for identifying determining mechanisms and probabilities are analogy analysis, technological sequence analysis, stakeholder analysis (Vanston 1995), and structural analysis. In trend impact analysis, surprise-free forecasts are adjusted to accommodate the expected impact of determining mechanisms (Gordon 1994b). Using cross-impact analysis (Gordon 1994c), probabilistic systems dynamics (Monte Carlo models), engineering-economic models and equilibrium models, the combined effects of several trends can be studied.

Participatory methods seek the insight and opinions of experts and stakeholders. They are based on the belief the future is shaped by complex mixture of trends, random events and actions of individuals and institutions. Therefore, to forecast the future, the insight and opinions of experts and stakeholders are seen as more useful than rational methods. The results of these methods are often more normative (what the future should be) than analytic (what the future is likely to be). However, analytical and modelling methods may provide input to guide participatory methods and the results from participatory methods may be used as inputs in modelling methods. Participatory methods are mainly relevant in complex situations, whereas in simple situations with a high degree of control, stakeholder involvement may be an unnecessary complication. Participatory methods range from the more structured Delphi technique (Gordon 1994d), scanning (Gordon & Glenn 1994), focus groups, charrette, Syncon, and future search conferences (Glenn 1994d) to the less structured methods relying more on subjective judgement, such as genius forecasting, intuition and visioning (Glenn 1994e).

Exploratory methods seek to structure all possible futures by combining analytic techniques, which give an exhaustive qualitative description of the field, with imaginative techniques aimed at filling all gaps in the analytical structure. In this way, possibilities rather than probabilities are considered. This may be useful in product development, for those processes upon which the decision-maker has a large potential influence. Morphological analysis, relevance trees, mind mapping and future wheel belong to this category (Futures Group 1994b, Glenn 1994c).

Normative (or goal-oriented) forecasting begins with stating the desired future and then moves backwards in time to identify the necessary steps for reaching this goal (Coates 1994). Besides this particularity, any of the above mentioned methods might be applied also in normative forecasting. Like exploratory methods, normative forecasting may be useful in product development, for those processes upon which the decision-maker has a large potential influence. Backcasting is an important member of this category.

Scenario methods include and combine aspects of the other methods, especially participatory, modelling and exploratory methods, with the aim of creating several distinct scenarios. They are based on the belief that the future is essentially unpredictable and largely random. Considering the uncertainties, modelling will not lead to one future, but rather to many different futures, each of which may be described in the form of a scenario (Futures Group 1994c).

Table 6.2. Relevance of forecasting methods depending on time horizon and complexity

	Forecasts for specific processes, when no radical or untypical developments are expected, or where such developments are under the control of the decision maker	Forecasts for less predictable processes and more complex systems
Long term (5-25 years)	Modelling, exploratory and normative methods	Scenario methods
Short-medium term (1-5 years)	Extrapolation methods	Modelling and participatory methods

The divisions in table 6.2 should be seen as guiding only. In practice, the distinction between the different situations and relevant methods is not sharp, and more than one method may be relevant in a specific situation. Often, different methods can be combined to give a more reliable forecast (see section 6.2).

6.5 Forecasting by extrapolation

Extrapolation is the simple (linear or non-linear) prolongation into the future of historical relations.

While all time series of data may be extrapolated, it is not all data that it is meaningful to extrapolate. To improve the reliability:

- The extrapolation should preferably be based on the determining factor for the expected development and the trend of this factor.
- Data for an extrapolation should at least go five years back, preferably 10 years. However, when radical changes have taken place, which have altered or radically influenced the determining factors, it does not make sense to include data from before such changes.
- Any constraints on the extrapolation should be taken into account (e.g. physical or political boundaries for the development of the extrapolated factor). When approaching a constraint, the extrapolation will no longer be a good approximation.

Some general conclusions from empirical observations may be applied:

- The introduction of a new technology tends to follow an S-curve, so that the initial penetration is slow but with a logarithmic increase, followed by a linear growth again followed by a logarithmic decrease in cumulative penetration until the market is saturated.
- Production costs tend to decrease with cumulative production capacity, following a so-called ***learning curve***, a logarithmic curve typically described by a ***learning factor***, which is the cost reduction achievable by doubling the cumulative production. The learning factor, which tends to be fairly stable for each specific technology, is typically between 0.9 and 0.75, meaning a cost reduction of 10-25% when doubling cumulative production. More innovative technologies tend to have the lowest learning factors (largest cost reductions) compared to more established technologies, which also implies that the learning factor ***does*** change when seen over very long time horizons. The learning curves for cost reductions mainly reflect savings in manpower, but physical efficiency improvements also play a role. Karvonen (2000) show a good correlation between gross emissions and cumulative investment in the Finnish pulp and paper industry, and Pento & Karvonen (2000) show that emission ***coefficients*** are even closer related to cumulative investments. Therefore, conservative learning factors (i.e. 0.85 - 0.95) may be used as proxies when estimating the physical flows in a life cycle study when the physical efficiency improvements in these flows are not known from other sources. Also in energy models, learning curves have recently gained more widespread use (Mattsson 1997, Mattsson & Wene 1997, IEA 2000a, Pehnt 2001)

Sources of time series may be:

- Technical literature and technical experts on the process in question.
- Statistics of industrial associations.
- General statistical publications.

Kakudate et al. (2000) provide an LCA-relevant example of extrapolation of copper contamination of steel based on steel production statistics, the lifetime of steel products, and national recycling, import, and export rates.

An extrapolation is not necessarily quantitative, but can be e.g. a text description of the consequences of extending the prevailing trends into the future.

Limitations of extrapolation in forecasting

Since extrapolation is based on historical data alone, and does not include combined effects of several developments, it can only be used for medium or short-term forecasts for smaller, specific areas, where no radical or untypical developments are expected.

In spite of its limitations, an extrapolation is a better forecast than an assumption of status-quo. Thus, even when there is no time or resources to involve technical experts, it may be justified that a non-expert makes a simple extrapolation as a first approximation.

6.6 Forecasting by modelling

Modelling is the analysis of the interactions of several cause-effect mechanisms over time, depending on their relative strengths and probabilities of occurrence.

Modelling is based on an identification of relevant mechanisms, their probabilities of occurrence, and their interactions. In this way, otherwise surprise-free forecasts are adjusted to accommodate the expected interactions of determining mechanisms.

Many of the publicly available forecasts for more complex systems (concerning e.g. electricity production, disposal, collection of waste etc.), as provided by governmental bodies or industry organisations, are based on modelling. Models can be divided in bottom-up engineering-economic models (such as European Commission 1995a, Mattsson 1997, Mattsson & Wene 1997, Stein & Wagner 1999, Kram et al. 2001, Gielen & Moriguchi 2001), and top-down macroeconomic and general equilibrium models such as those used by IEA (2000b). Jochem (1999) delivers a critique of engineering-economic models compared to top-down models and conclude: "Top-down [modelling] communities have far too little knowledge imbedded with regard to technological change, saturation in high income economies, and structural change. Engineering-economic modellers, on the other side, have little to say on the influence of rebound effects or income effects, which may be very important in specific target groups (e.g. private households)," and recommend a better integration of the communities of engineering-economic and top-down modellers. Walter-Jørgensen (1999) presents an interesting combination of technical analysis, farm-level economic analysis and use of a general equilibrium model in a study on phasing out of pesticide use.

Complex models as the ones mentioned above, cannot be explained in few words, and we therefore give only a few examples of more domain-specific models and applications:

Example: Modelling the energy use and emissions from transport
The energy consumption for transport per kg good may change over time depending on changes in:

- ***modal choice (ship, rail, truck, aeroplane),***
- ***transport distances,***
- ***vehicle sizes,***
- ***capacity utilisation,***
- ***traffic conditions,***
- ***combustion efficiency,***
- ***education and maintenance.***

Changes in emissions depend on all of the above plus changes in fuel composition and emission control. The interdependence of the different variables can be expressed in the form of equations, and a time series can be determined for the determining variables. This constitutes a model. Several such models of transport systems exist, e.g. as a result of the EU COST 319 action.

The following example shows a very simple, qualitative form of modelling, with only a few variables.

Example (from de Beer 1998):

Potential technologies for steel casting (identified through participatory methods, see section 6.1.6) are scored in a matrix according to their current stage of development and their degree of technical innovation compared to the currently applied technology.

	Degree of technical change:		
Stage of development:	*Small*	*Major*	*Radical*
Commercial	*Thin slab casting*	-	-
Demonstration	*Thin slab casting with liquid core reduction*	-	-
Experimental	-	*Strip casting*	*Spray casting*
Applied research	-	-	-

Supplemented by a consideration of costs and benefits (strip casting having the largest potential for energy savings), this modelling leads to placing the most probable future technologies (thin slab casting and strip casting) on a time series.

Limitations of modelling in forecasting
Since modelling include the combined effects of several developments, and is not based on historical data alone, it can more readily be used for forecasts with a longer time horizon.

Still, depending on the number of variables and the degree of uncertainty included in the modelling, it may result in oversimplification of the future. Thus, in studies that deal with less predictable processes and more complex systems, where the driving forces can work in many directions, modelling should be supplemented by participatory methods (see section 6.1.6), and for forecasts with a longer time horizon, several scenarios should be applied (see section 6.1.8).

Modelling will typically require the involvement of technical experts both for the identification of relevant mechanisms, their interactions, and their probabilities of occurrence. It may thus be too sophisticated for more simple situations (medium or short-term forecasts for smaller, specific areas, where no radical or untypical developments are expected).

6.7 Participatory forecasting

Participatory forecasting methods use the insight and opinions of experts and stakeholders to derive statements on the possibility and/or probability of future events and mechanisms and their interaction.

The insight and opinions of experts and stakeholders are derived:
- from scanning of published information,
- by questionnaire polling,
- from one-to-one interviews,
- from panels, in which different opinions are confronted.

These sources may also be used in combination.

Scanning of published information is the most neutral of the methods, but its scope is limited to the issues on which published information is available, and it does not allow interaction between the source and the inquirer. Questionnaire polling has the advantage of involving a larger and possibly representative group of people. One-to-one interviews provide more flexibility in soliciting arguments for the answers given, in searching for biases and contradictions, and in following unexpected lines of inquiry arising from the interview situation. Panel methods, in which the opinions of the participants are confronted, may be used both with an exploratory orientation, to stimulate creativity and divergence, and (more commonly) with a consensus-orientation, seeking to reach some degree of consensus among the panellists.

When selecting sources or participants for polling, interviews, or panels, more or less weight may be placed on involvement of:

- a representative group (typically the overall concern in questionnaire polling),
- different stakeholders (important when aiming at consensus),
- sources of interesting and extreme positions (important when the focus is more exploratory).

All participatory methods have an element of subjectivity, which may be countered in different ways:

- The selection of sources or participants may be biased, excluding certain stakeholders or extreme positions. This may be countered by letting the selection be done by one or more "neutral" third parties. It should be avoided that participants are excluded because of lack of resources or access to specific forms of communication (e.g. access to electronic mail or telephone services).
- Wording of questionnaires or the presentation of issues to interviewees or panellists can pre-determine the results. This may be countered by starting with more open questions, pre-testing the questions on a critical panel, and by including specific test-questions that address the same issue from a different angle. It should be avoided that participants are forced to answer questions that they do not feel qualified to answer.
- A human tendency to stay within traditional patterns of thought may be countered by specific mental techniques to stimulate new thoughts among participants.
- There is a tendency that participants answer questions in the way that they expect the interviewer to desire. Ensuring anonymity of participants may enhance their willingness to give controversial or extreme answers to questions. When working with panels, this may be further stimulated by group facilitation techniques such as simulations and games.
- Information on how others have answered the same questions, and possibly also their arguments for such answers, may stimulate revised answers or counter-arguments, especially when anonymity is ensured. Such repeated questioning with feedback and anonymity has become known as the Delphi-technique, which is very widely used e.g. for technological foresight programmes (Gupta & Clarke 1996, Georghiou 1996).

Forecasts resulting from participatory techniques are quite often available in published form.

Limitations of participatory methods

Participatory methods are especially relevant when dealing with controversial or complex aspects of a life cycle study. Several opinions may be heard, including more extreme positions, which may be disregarded by more analytical methods such as modelling. When stakeholders are involved, participatory methods may furthermore increase the probability of acceptance of the results from a life cycle study and thus speed up the following implementation.

However, because of their subjective elements, participatory methods may still be seen as unacceptable both by those who feel unable to influence the result and by those who see the participatory process as endangering to their established power.

Also, participatory methods are quite time consuming and difficult to apply, and will therefore be too sophisticated for more simple situations (medium or short-term forecasts for smaller, specific areas, where no radical or untypical developments are expected).

6.8 Exploratory and normative forecasting

For processes upon which the decision-maker has a large degree of (potential) influence, and especially in the context of product development, it may be more interesting to examine how the future could be (using exploratory methods), or how it should be (using normative methods), than how it is likely to be (using analytical methods, such as modelling).

Exploratory methods concentrate on structuring possible futures, typically using qualitative descriptions. Exploratory methods combine analytic techniques that branches a broad topic or development into increasingly smaller subtopics or consequences, and imaginative techniques aimed at filling all gaps in the analytical structure. In this way, the full field of possibilities is identified and structured, providing a multitude of combinations and permutations as a starting point for e.g. product development. This large number of possibilities may afterwards be reduced according to economic, technical, and strategic criteria, summarised as e.g. breakthrough potential and importance to the decision-maker.

An example of an exploratory method for use in product development is TRIZ, a commercial method that combines analogy and morphological analysis (Kowalick 1997, Arciszewski & Zlotin 1998). TRIZ is based on systematic analysis of patents from which a number of principles of innovation and "laws of evolution of engineering systems" were derived (Altshuller 1984). Morphological analysis is used to identify the essential functions of the investigated product and the possible solutions for specific functions. These possible solutions are then combined with the innovation principles and the above statements or "laws" to point out the most relevant future solution. In TRIZ, functions and methods have been collected in a database. The TRIZ database is usually used in product development but it can also be used for technological forecasting by simulating the product development.

Normative (or goal-oriented) forecasting investigates how we want the future to be and how to obtain this goal. In contrast to e.g. modelling, which investigates possibilities and probabilities and generally moves forward into the future in terms of forces at play, normative forecasting states objectives that may be substantially discontinuous with the trends at play, then moves backwards to the present to identify the necessary steps for reaching the objectives. Besides this particularity, any of the other forecasting methods may be applied also in normative forecasting. Normative forecasting is at the heart of organisational planning. It allows an organisation to orchestrate and target its resources to achieve a goal. The statement of the goal itself must be realistic and take into account present and future resources and contexts. A crucial part of a normative forecast is the detailed analysis, which reveals the specific steps that must be taken at specific times.

Exploratory and normative forecasting require a detailed knowledge of the involved organisation and technical field. It must therefore be performed in close co-operation with knowledgeable people in the organisation. The involvement of the decision-makers is essential in the criteria-setting stage of exploratory forecasting and the goal-setting stage of normative forecasting.

Technology roadmaps are one result of exploratory normative forecasting. Examples are Eisenhauer et al. (1997), Semiconductor Industry Association (1999).

Limitations of exploratory and normative forecasting
Exploratory and normative forecasting are only relevant methods for processes upon which the decision-maker has a large degree of (potential) influence, so that the necessary steps can be taken to reach the forecasted (selected) goal. It may be tempting to place unrealistic confidence in the potential influence of the decision-maker, and to place to little emphasis upon outside influences.

Exploratory methods may yield an overabundance of possibilities, which makes it difficult to identify which of the possibilities are the most relevant.

6.9 Scenario forecasting

For long-term forecasts in complex situations where many interdependent forces are at play, it is unlikely that a specific forecast can be identified as the single “most likely” description of the future. Instead, scenario methods aim at presenting a broad range of plausible outcomes (scenarios), which can serve as a basis for robust conclusions that are viable over the wide range of possible futures.

The term “scenario” comes from the dramatic arts, where a scenario refers to an outline of the plot. In forecasting, a scenario is an integrated, coherent, and consistent narrative description of a plausible future situation, often including a description of the development from the present to the future to focus attention on causal processes and decision points.

Often scenarios are based on modelling, displaying the conditions of important variables over time, thereby giving a quantitative underpinning of the narrative description. The nature of evolutionary paths are especially relevant when scenarios are used directly in decision making, since decisions can deflect those paths. However, a scenario does not have to be based on a model, but can be a simple description of a situation.

One scenario usually represents a surprise-free continuation of the present forces at play. Other scenarios are typically based on extreme optimistic and/or extreme pessimistic developments in one or more of the particularly important cause-effect mechanisms (typically technological, political, economical or sociological mechanisms). In general, three to six scenarios are sufficient to capture the range of future possibilities.

Scenario methods are widespread and many good examples have been published (see e.g. UN 1990, Gallopin et al. 1997, WBCSD 1998, Glenn &

Gordon 1998). General scenarios for use in life cycle assessments may be derived from such published sources, e.g. the model-based energy scenarios of the EU (European Commission 1996). A scenario methodology for use in product design, with both participatory and normative elements, is described by Manzini & Jégou (2000), see also Partidário & Vergragt (2000).

When there are no resources to produce case-specific scenarios, default scenarios may be applied instead. Three scenarios are described below, which represent three extreme perspectives. These three perspectives are commonly used for scenario building (see e.g. the FROG, GEOpolicy, and Jazz scenarios in WBCSD 1998). A theoretical foundation for the three perspectives is provided by three active archetypes of the socio-cultural viability theory (Thompson et al. 1990, Hofstetter 1998): the individualist, the hierarchist, and the egalitarian archetype.

For system delimitation, the important difference between the three perspectives concerns the degree of market regulation and the acceptability of environmentally induced change, see table 6.3:

- The individualist perspective calls for solutions based on free market economy, implying few regulations on competition and a general growth in production, which seeks to take environment into account through innovation and integration into the market mechanisms.
- The hierarchist perspective calls for solutions based on globally coordinated regulation and controlled growth that takes into account environmental externalities in the decision-making.
- The egalitarian perspective calls for solutions based on local regulation that radically change patterns of production and consumption to a sustainable level.

The consequence for system delimitation in LCA is summarised in table 6.3 and an example of how this influences the choice of electricity scenarios in Europe is provided below.

Table 6.3 The consequence of the three default cultural perspectives on the assumptions used in LCA system delimitation

Cultural perspective: Default assumptions regarding:	**Individualist**	**Hierarchist**	**Egalitarian**
Ties between companies	Few	Forced	Many
Market segmentation	Low willingness to substitute very different products	Substitution may be forced when necessary	High willingness to substitute very different products
Geographical markets	Global trade only restricted by transport costs and availability	Regulated markets	Localised markets
Market trend	Growing	Controlled growth	Stagnating to decreasing
Production constraints	Only for co-products with a low value relative to the remaining co-products from the same process	Quotas apply	Strict quotas apply
Important factors for decisions on capital investment	Competitiveness, mainly determined by labour costs and skills required	Externalities included in decisions	Production costs play a minor role for decisions

Example: Supply of additional European electricity in the three default cultural perspectives

In the individualist scenario, an additional demand for electricity will be supplied from the free market, which will be a growing, deregulated European market (only restricted by the physical limits for transmission), where the transmission capacity has been expanded to allow all producers to compete on equal terms. In this scenario, the highly competitive fossil fuels will continue to be the main source of additional power. Emission quotas do not play any significant role in restricting the use of coal, but the high capital requirements of coal-based technology may allow gas-based technology to gain a considerable market share. Innovation will mainly be driven by an interest in decreasing production costs through more efficient combustion (e.g. in fuel cells).

In the hierarchist scenario, the market is regulated to include environmental externalities in the decision-making, which strives for an optimal balance between societal costs and benefits. This implies the use of tradable emission permits or emission taxes. An additional demand for electricity will be supplied by that power plant which in the given situation has the lowest production costs, taking into account the environmental externalities as translated through taxes and permits. This will place wind power very favourably, as long as acceptable solutions can be found to its localisation. The resulting electricity scenario is a mix of wind power with local biomass and regional natural gas as stabilising technologies.

In the egalitarian scenario, the electricity demand will be stagnating due to a mix of increased efficiency and savings in consumption. Transmission capacity will be limited, as each region relies on its own production capacity. Nuclear power and fossil fuels has been phased out, leaving the electricity to be supplied by combustion of biomass and waste, hydro-, wind and solar sources. A certain loss of supply stability will be accepted. Since production costs play only a minor role for decision-making, a change in demand for electricity will affect the local supplier with the least environmentally benign technology, which in most cases will be the plants based on biomass combustion, although hydro-power facilities may also be affected in mountain regions.

Limitations of scenario methods

Scenario forecasting may be unnecessarily sophisticated for medium or short-term forecasts and more specific, uncomplicated situations.

6.10 Consistency check

Within the same life cycle study, different forecasting methods may be appropriate for different parts of the product systems. This is not in itself an inconsistency, as long as the choice of method is justified and the specific assumptions used in the different methods are not inconsistent.

Even when the same method is applied throughout a study, it should be checked that assumptions and results are used in a consistent manner.

6.11 Combining different forecasting methods

Applying more than one forecasting method can be a way of validating the assumptions and/or outcome of each individually applied method. In particular:

- For an extrapolation, the outcome of modelling may be used to validate the relationship between different trends used, and the identification of which trends are determining and directly related to the time axis.
- An extrapolation or model may be validated by participatory methods (e.g. asking experts), which may also provide reasons that the extrapolation or model should be adjusted, e.g. due to expected legislation, economical changes or other initiatives that might affect the extrapolated trend or the modelled relations.
- Results of participatory methods are often more normative (what the future should be) than analytic (what the future is likely to be). Modelling may give a more analytical perspective on a result from participatory methods.

The outcome of one forecasting method may be used as input in other methods. In particular:

- As an input to modelling, an extrapolation may be used as one of more basic mechanisms or equations in a model, and participatory methods may provide information on causal relations and probabilities of events and mechanisms, and interaction between mechanisms.
- In extrapolation and modelling, the insights from exploratory methods may be used to ensure that all important aspects have been taken into account.
- In participatory and scenario methods, an extrapolation can be used as a surprise-free base-line forecast ("suppose things keep going as they have in the past ...") to be modified.
- In participatory methods, the results of practically all other forecasting methods may be used when designing topics and questions, or directly for the participants as background information for questions or as a common input to which they can relate.
- Normative forecasting may apply both the methods and results of any of the other forecasting methods. Especially modelling techniques may be useful during the "backtracking" step, but even extrapolations can be applied “in reverse”.
- In scenario methods, results from modelling, participatory and normative methods may be used as (part of) one or more scenarios.

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Annex A. Avoiding co-product allocation in a simplified hypothetical refinery[22]

The refinery and its product flows are illustrated in figure A

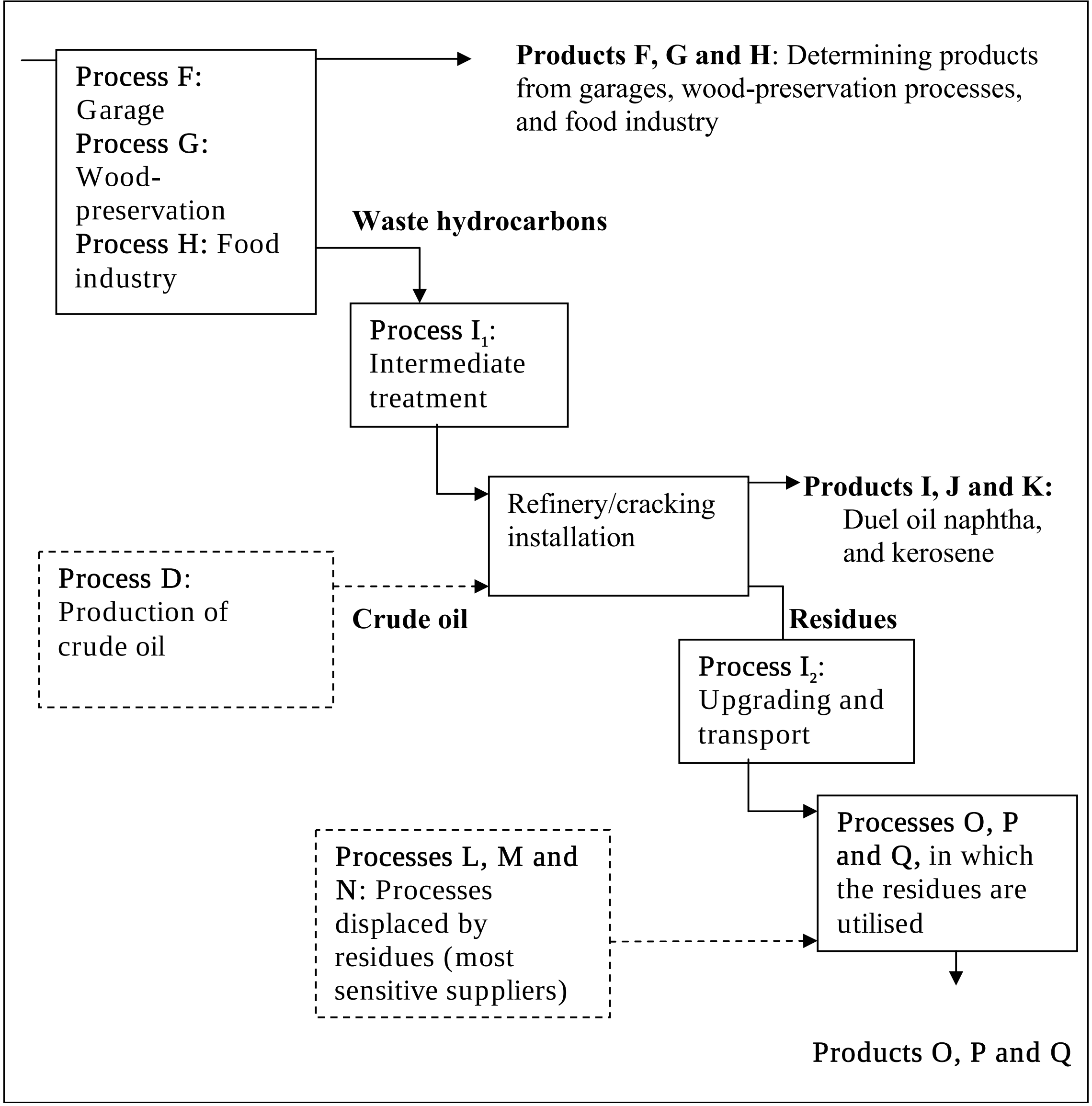

Figure A.1 The expanded product systems related to the refinery/cracking installation

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[22] The elaboration of this example was financed by the Dutch methodology project and originally published in their report (Guinée et al. 2001, part 2b, pp. 36-41).

A.1 Identification of the economic inputs and co-products

The refinery has:

- Three independently variable economic inputs:
    - Waste lubricants from garages
    - Waste hydrocarbons from wood preservation
    - Waste hydrocarbons from food industry

  These inputs are variable in the sense that they are not needed for the process and may therefore be varied depending on supply.
- One dependent economic input:
    - Crude oil

  This input is dependent in the sense that its volume depends on the volume of the variable inputs and outputs.
- Three independently variable economic outputs:
    - Fuel oil
    - Naphtha
    - Kerosene

  Within the technical limits, these outputs are variable depending on demand. If technical limits are encountered at the specific refinery investigated, the change in demand will lead to changes in the production of a similar refinery without these technical limits. When studying changes that are so large that the technical boundaries of the entire refinery industry are encountered, it is necessary to regard these outputs as dependent. We assume here, that the studied change is small.
- Three dependent economic outputs:
    - Long residues
    - Mixed residues for upgrading
    - Mixed residues for incineration

  These outputs are sought minimised and thus depend solely on the volume of the inputs and the variable outputs

A.2 Independently variable economic inputs

For the ***independently variable economic inputs*** (waste lubricants and other hydrocarbons) the following conditions apply (irrespectively of the economic value of the input):

- ***Upstream processes:*** The volume of these inputs depends on the volume of the upstream processes (processes F, G and H in figure A.1) of which these inputs are wastes, not on the volume of the refinery production. The refinery acts as a waste treatment for these inputs. The wastes are assumed fully utilised (since they are valuable as inputs to the refinery and the total amount available on the market does not exceed that which can be used by the refinery industry). Thus, the upstream processes are not relevant for the other refinery co-products, i.e. there is a clear cut-off at the incoming refinery gate.
- ***Avoided processes:*** The production of the crude oil displaced by the variable inputs (process D in figure A.1) is credited to the main products of the upstream processes of which these inputs are wastes (i.e. the products of the garages, wood preservation processes and food industry).
- ***Other effects on the refinery and downstream processes:*** If the input causes any changes in the environmental exchanges from the refinery or further

downstream processes, compared to the use of crude oil as a raw material, these changes are ascribed to the main products of the upstream processes of which these inputs are wastes (i.e. the products of the garages, wood preservation processes and food industry). This may for example be due to the nature of the waste (the hydrocarbons from food industry may be vegetable, which e.g. may lead to lower VOC emissions than from comparable fossil raw materials) or due to contamination (e.g. heavy metals from the lubricant use or wood preservation).

To determine the environmental exchanges to be ascribed to the products of the garages, wood preservation processes and food industry (products F, G and H in figure A.1) the following information on the system is needed:

1) Changes in the economic outputs when changing the independently variable inputs (waste lubricants and other hydrocarbons): We assume that there is no change in the independently variable outputs (fuel oil, naphtha, kerosene), since such changes would be undesirable for the refinery, and would thus be avoided by reducing the variable inputs accordingly. We assume that the independently variable inputs (waste lubricants and other hydrocarbons) do not give rise to outputs of long residues and mixed residues for incineration, since these inputs have already been processed once.
2) The amount of crude oil displaced by the independently variable inputs (waste lubricants and other hydrocarbons): We assume that the hydrocarbon chains of these inputs are of similar composition as crude oil, with the exception mentioned under 1) that they do not contain the fractions that give rise to outputs of long residues and mixed residues for incineration. This leads to a slightly lower requirement of crude oil per input of waste hydrocarbons: 1 kton waste hydrocarbons yields 0.91 kton of the outputs fuel oil, naphtha, kerosene and mixed residues for upgrading (12 kton waste – 9.375% process loss), while 1 kton crude oil gives only 0.66 kton of these products (20 kton – 9.375% process loss – 5 kton long residues and mixed residues for incineration). Thus, 1 kton waste hydrocarbons displaces 1.38 kton crude oil. As can be seen from this calculation, we have assumed that the process loss (mainly feedstock used for fuel) does not depend on the type of input. If the waste hydrocarbons do not need as much processing as crude oil (or need more processing), this assumption should be changed accordingly, which will also lead to a change in the amount of crude oil displaced.
3) Changes in the environmental exchanges from the refinery when changing the independently variable inputs (waste lubricants and other hydrocarbons), compared to the use of crude oil as a raw material: The emissions from the refinery can largely be divided in emissions from combustion related to the use of process energy, emissions of VOC, and solid and liquid wastes. The combustion emissions depend on what processes the different raw materials require. We have assumed that there is no change in energy requirement (see point 2), and thus no change in combustion emissions. For VOC emissions from the from the waste hydrocarbons, it is reasonable to assume that there will be no emissions of methane (compared to 42 kg per kton crude oil) and fewer emissions of the lighter VOCs (we assume a 10% reduction from the 380 kg per kton crude oil), since these inputs have already been processed once. If it is assumed that any contaminants in the waste hydrocarbons are either degraded during processing or left in the product outputs (see point 4), also the solid and liquid wastes can be assumed linked to the crude oil only.

4f) Changes in the environmental exchanges from downstream processes when changing the input of waste lubricants from garages, compared to the use of crude oil as a raw material: Heavy metal contaminants (assumed 20 kg/kton) will be suspended in proportional amounts in all economic outputs, except the lightest fraction (mixed residues to incinerator). For the fuel fractions (fuel oil and kerosene) this will eventually end up as air pollution from the combustion. Heavy metal contaminants in the naphtha will end up in the products produced from this (plastics) and will be released from waste treatment of these products (we assume combustion). Heavy metal contaminants in the long residues will probably be fixed in the resulting products (asphalts etc.).

4g) Changes in the environmental exchanges from downstream processes when changing the input of waste hydrocarbons from wood preservation, compared to the use of crude oil as a raw material: If the waste contains any heavy metals, these will have the same fate as indicated under 4f). If the contaminants are organic, we assume that they are decomposed during the refinery processing.

4h) Changes in the environmental exchanges from downstream processes when changing the input of waste hydrocarbons from food industry, compared to the use of crude oil as a raw material: We assume that this will not cause any changes in downstream processes.

Furthermore, the following information on the environmental exchanges from each of the involved processes are needed:
Process F, G, H and I_1: In this context, we do not use real data for these processes.
Process D (crude oil production, incl. transport): For this, standard literature data (ETH) can be used. In this example, we limit the calculation to include the following emissions (per kton crude oil):
CO_2: 120 ton
Methane: 10 ton
NMVOC: 73 ton

The calculation to be made is (normalised to 1 kton of waste hydrocarbon input to the refinery): Environmental exchanges to be ascribed to products F, G and H, respectively = (Environmental exchanges from process F, G or H, respectively) – (Environmental exchanges from production of 1.38 kton crude oil) – (Refinery emissions of methane, lighter VOCs, solid and liquid wastes equivalent to 1.38 kton crude oil input) + (Downstream emissions of heavy metals equivalent to the difference in heavy metal content between the waste hydrocarbon and crude oil).

For waste hydrocarbons from wood preservation, the result is presented in table A.1 (not including the environmental exchanges from the wood preservation process itself).

Table A.1 Calculation of selected environmental exchanges to be ascribed to waste hydrocarbons from wood preservation (per kton waste hydrocarbon input to the refinery)

Emissions to air	I: Production of 1.38 kton crude oil	II: Refinery VOC emissions per 1.38 kton crude oil	III: Downstream emissions of Cd from contamination	To be ascribed to waste hydrocarbon per kton input: III – I –II
Cadmium	-	-	20 kg	20 kg
CO_2	166 ton	-	-	- 166 ton
Methane	14 ton	42 kg (i.e negligible)	-	- 14 ton
NMVOC	100 ton	38 kg (i.e negligible)	-	-100 ton

Provided more information on the different waste hydrocarbons, the above assumptions and the calculation result can be refined.

A.3 Independently variable economic outputs

For the ***independently variable economic outputs*** (fuel oil, naphtha, kerosene), the following conditions apply:

- ***Upstream processes:*** The dependent input (crude oil) will vary according to overall variations in the outputs.
- ***Refinery:*** The environmental exchanges of the refinery may vary according to the composition of the output, since different processing routes are involved.
- ***Residues:*** The amount of residues are mainly determined by the raw material composition, but minor variations may be caused by changes in the output composition. The amount of residues may thus be calculated individually for each of the variable outputs. The residues are assumed fully utilised, so that any intermediate treatment (upgrading and transport) of the residues before they can displace other products are ascribed to the independently variable outputs in proportion to the amount of residues caused by each output (irrespectively of the economic value of the residues).
- ***Avoided processes:*** The processes displaced by the residues (processes L, M and N in figure A.1) are credited to the variable outputs in proportion to the amounts of residue caused by each output (irrespectively of the economic value of the residues).

To determine the environmental exchanges to be ascribed to the independently variable economic outputs (products I, J, and K in figure A.1), the following information on the system is needed:

The amount of crude oil corresponding to a change in the independently variable economic outputs: We assume the same amount of crude oil input irrespectively of the relative composition of the independently variable economic outputs.

The environmental exchanges of the refinery corresponding to a change in the independently variable economic outputs: The combustion emissions will increase when additional processing is needed to produce more of a fraction than what is the result of one crude distillation and one cracking of the distillation residue. The processing requirement depends on the composition of the raw material input. The relations given in the ETH data can be used to calculate the emissions per type of refinery output, unless more specific data are available.

The amount of residues caused by a change in the independently variable economic outputs: The amount of residues (especially the lighter residues) will increase slightly when additional processing is needed to produce more of a fraction than what is the result of one crude distillation and one cracking of the distillation residue. The processing requirement depends on the composition of the raw material input.

Furthermore, the following information on the environmental exchanges from each of the involved processes are needed:

Process D: (as above)

Process I_2: We assume that upgrading of long and mixed residues will lead to emissions in the order of 20% of the general refinery emissions. For mixed

residues for incineration, only the pumping to the incinerator is relevant (but assumed to be negligible).
Process L: The displaced process is either a dedicated bitumen production, or a change in the composition of the raw material input at a refinery having bitumen as an important product, resulting in a similar change in bitumen output. We assume that 0.17 kton of bitumen is displaced per kton of the independently variable economic outputs.
Process M: Parallel to process L, we assume the displacement to be accommodated by a change in the composition of the raw material input at a refinery having the upgraded product as an important product. We assume that 0.09 kton of other refinery products are displaced per kton of the independently variable economic outputs.
Process N: The displaced process is production and supply of fuel oil or natural gas, depending on the local supply situation. We assume that 0.85 TJ of natural gas is displaced per kton of the independently variable economic outputs.

The calculation to be made is (normalised to 1 kton of the independently variable economic outputs (fuel oil, naphtha, kerosene): Environmental exchanges to be ascribed to fuel oil, naphtha and kerosene, respectively = (Environmental exchanges from production of 32/29 kton crude oil) + (Refinery emissions related to the output in question, cf. ETH) + (Environmental exchanges from upgrading of the amount of long and mixed residues that can be related to the output in question, cf. ETH) – (Environmental exchanges of the processes displaced by the residues that can be related to the output in question, cf. ETH).

For kerosene, the result is presented in table A.2 (not including the environmental exchanges from the wood preservation process itself).

Table A.2 Calculation of selected environmental exchanges to be ascribed to kerosene (per kton kerosene output from the refinery)

Emissions to air	I: Production of 32/29 kton crude oil	II: Refinery emissions related to kerosene	III: Upgrading of the amount of long and mixed residues that can be related to kerosene	IV: Processes displaced by the residues that can be related to kerosene	To be ascribed to kerosene per kton output: I + II + III - IV
CO_2	132 ton	9 ton	1.8 ton	38 ton	105 ton
Methane	11 ton	0.04 ton	0.004 ton	2.8 ton	8.2 ton
NMVOC	81 ton	0.5 ton	0.05 ton	18 ton	64 ton
NO_x	-	28 kg	6 kg	25 kg	9 kg
SO_2	-	470 kg	94 kg	138 kg	425 kg

A.4 Dependent economic outputs

The ***dependent economic outputs*** (different residues) are utilised fully in other processes. Thus, a change in demand for these residues will affect the same processes as those displaced by the residues (processes L, M and N). These processes are therefore ascribed to the product in which the residues are utilised (irrespectively of the economic value of the residues).

To determine the environmental exchanges to be ascribed to the products in which the residues are used (products O, P and Q in figure A.1), the environmental exchanges from the following processes must be known:
Process L, M and N: (as above)

Process O, P and Q: In this context, we do not use real data for these processes.

The calculation to be made is (normalised to 1 kton of the residue): Environmental exchanges to be ascribed to the product in which the residue is utilised = (Environmental exchanges from process O, P or Q, respectively) + (Environmental exchanges of the process L, M or N, respectively).