Chapter 9
Life Cycle Inventory Analysis

Anders Bjørn, Andreas Moltesen, Alexis Laurent, Mikołaj Owsianiak, Andrea Corona, Morten Birkved and Michael Z. Hauschild

Abstract The inventory analysis is the third and often most time-consuming part of an LCA. The analysis is guided by the goal and scope definition, and its core activity is the collection and compilation of data on elementary flows from all processes in the studied product system(s) drawing on a combination of different sources. The output is a compiled inventory of elementary flows that is used as basis of the subsequent life cycle impact assessment phase. This chapter teaches how to carry out this task through six steps: (1) identifying processes for the LCI model of the product system; (2) planning and collecting data; (3) constructing and quality checking unit processes; (4) constructing LCI model and calculating LCI results; (5) preparing the basis for uncertainty management and sensitivity analysis; and (6) reporting.

Learning Objectives
After studying this chapter the reader should be able to:

- Collect and critically evaluate the data quality of an LCI.
- Construct a unit process from first-hand gathered data.
- Build an LCI model using either attributional or consequential approach and explain the differences between the two approaches.
- Explain what data is required for uncertainty and sensitivity analyses and how to collect these data.
- Document an LCI model, including unit processes and LCI results.

A. Bjørn (✉) · A. Moltesen · A. Laurent ·
M. Owsianiak · A. Corona · M. Birkved · M.Z. Hauschild
Division for Quantitative Sustainability Assessment, Department of Management
Engineering, Technical University of Denmark, Kongens Lyngby, Denmark
e-mail: anders.bjoern@polymtl.ca

A. Bjørn
CIRAIG, Polytechnique Montréal, 3333 Chemin Queen-Mary, Montréal, QC, Canada

M.Z. Hauschild et al. (eds.), *Life Cycle Assessment*,
DOI 10.1007/978-3-319-56475-3_9

9.1 Introduction

During the life cycle inventory (LCI) analysis phase of an LCA the collection of data and the modelling of the flows to, from and within the product system(s) is done. This must be in line with the goal definition (see Chap. 7) and (to the extent possible) meet the requirements derived in the scope definition (see Chap. 8). The LCI result is a list of quantified elementary flows crossing the system boundary of the studied life cycle and it is used as input to the subsequent LCIA phase (see Chap. 10). Insights that the LCA practitioner gains when conducting the LCI analysis are also commonly used to adjust the requirements of the scope definition, e.g. when unforeseen data limitations lead to the need for a modification of the completeness requirements (see Sect. 8.6.3). Typically, the LCI analysis is the phase that requires the most efforts and resources from the LCA practitioner, and it is rarely practically possible to collect the highest quality of data for all processes of the LCI due to the unreasonable high cost that would be involved. Fortunately, it is also rarely needed in order to meet the goal and support the intended applications of the LCA. Therefore, the inventory analysis requires a structured approach to ensure that time is being spent on collection of data for those parts of the product's life cycle that are most important for the overall impacts from the product system. Several iterations between the LCI and LCIA phase are normally needed to meet the goal of the study, with each iteration providing insight into which inventory data are the most important for the LCA results (see Chap. 6).

In this chapter, we provide practical guidance on how to perform an LCI analysis using an iterative approach to LCA. We will focus on providing detailed guidance for the four decision contexts (A, B, C1 and C2) in line with the ILCD guideline. The chapter is structured around six steps of an LCI analysis:

1. Identifying processes for the LCI model
2. Planning and collecting data
3. Constructing and quality checking unit processes
4. Constructing LCI model and calculating LCI results
5. Preparing the basis for uncertainty management and sensitivity analysis
6. Reporting.

Before digging into the details, we note that this chapter teaches how to construct an LCI using knowledge about the industrial processes taking part in a life cycle and the physical flows connecting them. This is called a process-based (or bottom-up) approach to inventory modelling. A complementary approach to constructing an LCI is to model the life cycle inventory for the product from a macroscale perspective by drawing on a combination of (1) information on elementary flows associated with one unit of economic activity in different sectors and (2) national statistics on the trade of products and services between sectors. This is called environmentally extended input–output analysis (EEIO) and in contrast to the process-based approach it can be seen as a top-down approach to inventory modelling. The strength of EEIO is that a completeness of 100%, in theory, can be achieved in the sense that no processes need to be cut-off due to missing data or budget constraints. The two main weaknesses of the EEIO approach are (1) that the coverage of elementary flows is rather limited, compared to the process-based approach and that (2) the resolution of many products and services is quite low due to the heterogeneous nature of many sectors, as defined by national trade statistics. Chapter 14 deals with IO-LCA and in particular how to use EEIO to complement and guide process-based LCA. This chapter will make references to EEIO, when the approach can complement the process-based approach.

9.2 Identifying Processes for the LCI Model

This first step of *the LCI details the coarse* initial system diagram made under the scope item System boundaries (see Sect. 8.6) and draws upon the related completeness requirements. The outcome of the step is a detailed depiction of the foreground system, i.e. all the processes it is composed of and their links, and the processes of the background system 'neighbouring' the foreground system, i.e. where links to LCI database processes will be established.

9.2.1 Detailing the Physical Value Chain

For all decision contexts (A, B, C1 and C2—see Sect. 7.4) the approach to identifying processes is to start with the reference flow and construct the entire foreground system process by process:

0. The unit process having the reference flow, as product output, should first be identified (or unit processes, in the case of more than one reference flow). This is termed a 'level 0' process. In a study where a window is the reference flow, the level 0 process is the assembly of the window.
1. The processes required to deliver flows that will be *physically embodied* in the reference flow should then be identified. These are termed "level 1" processes. In the window example, examples of level 1 processes are the production of glass and the window frame.
2. The processes required to deliver flows that perform a *supporting function* to the level 0 process (i.e. not becoming physically embodied in its output) should then be identified. These are termed 'level 2' processes. In the window example, examples of level 2 processes are the supply of electricity used in the assembly of the window or the transportation needed to deliver the flows of the level 1 processes to the level 0 process.
3. The processes required to *deliver services* to the level 0 processes should then be identified. These are termed 'level 3' processes. In the window example, examples of level 3 processes are administration and marketing.

4. The processes required to produce and maintain the *infrastructure* that enables the level 0 process should then be identified. These are termed 'level 4' processes. In the window example, examples of level 4 processes are production and maintenance (oiling, replacing and repairing parts) of the assembly machines.

After having identified level 1, 2, 3 and 4 processes belonging to the level 0 process (the reference flow), Step 1–4 is then repeated for each these processes. This procedure is illustrated in Fig. 9.1 for the window example.

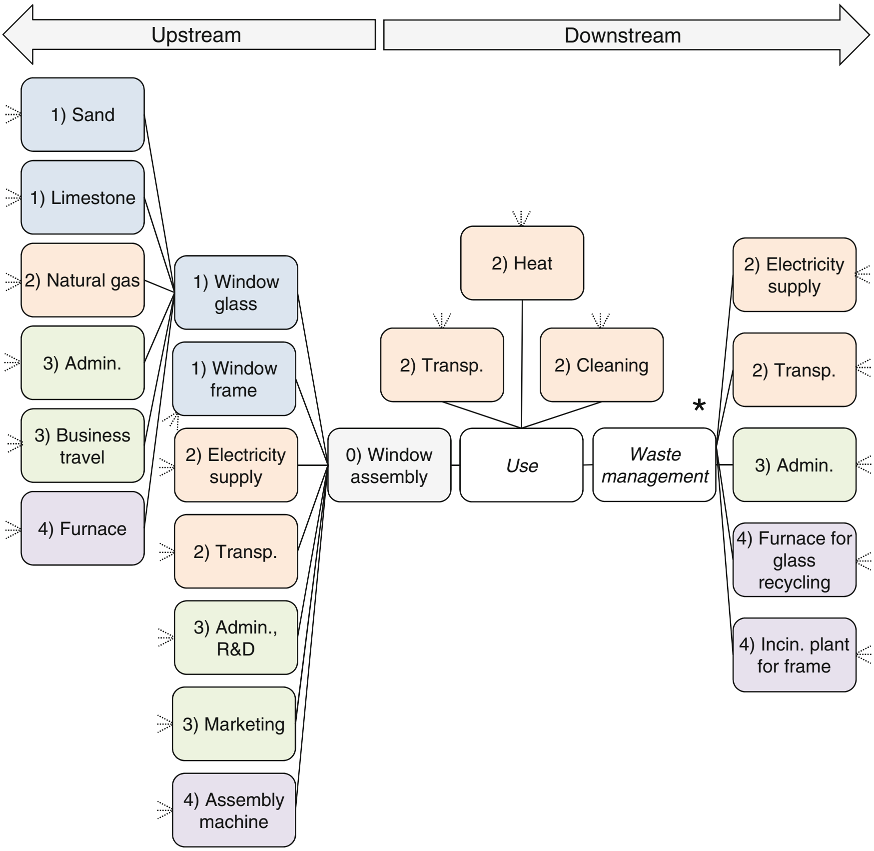


Fig. 9.1 Procedure for identifying processes of the foreground system, exemplified in the study of the life cycle of a window. The starting point is the process that delivers the reference flow, '0) Window assembly'. The foreground system is then populated process by process by proceeding upstream and downstream from the reference flow. *Unlinked arrows* present on some processes indicate the existence of other processes that were not included in the figure. Use and Waste management are in *italic*, because they represent life cycle stages, rather than actual processes. The *star* at 'Waste management' indicates the existence of multifunctional processes, i.e. glass recycling and incineration of window frame. *Abbreviations* in the figure: *Incin* incineration, *Transp* transportation, *Admin* administration, *R&D* research and development. *Numbering* and *colour code*, identify the process level for the different foreground processes

Processes downstream, i.e. in the use and waste management stages, should be identified in a similar fashion. The procedure is, in principle, repeated until the foreground system is completed and can be linked to LCI database processes of the background system, as described later in this chapter. When carrying out this procedure, the LCA practitioner should identify all multifunctional processes, because they have to be handled next.

Note that the step of identifying processes for the LCI model and the step of planning and collection of data are somewhat interrelated. For example, data collected for a given process may lead to the realisation that one or more upstream processes are different than the ones previously (assumed) identified. During data collection the LCA practitioner may, for example, realise that a plastic component is actually produced from biomaterials rather than petrochemicals, as was initially assumed. The identified processes in this first inventory step should therefore be considered preliminary.

In practice, many processes belonging to level 3 and 4 will end up being entirely omitted from an LCI model, because their individual contribution to the indicator score is expected to be insignificant and because data can be hard to find, at least when using the 'bottom-up' (=process-based) approach to constructing inventories. In such cases, the environmental impacts of product systems are systematically underestimated by various degrees. It is an important task of the inventory analysis and consecutive impact assessment to ensure that this underestimation does not violate the completeness requirements for the study. Chapter 14 shows how IO-LCA can complement process-based LCA to better cover the impacts from level 3 and 4 processes.

9.2.2 Handling of Multifunctional Processes

Section 8.5.2 presented the ISO hierarchy for solving multifunctionality, i.e. processes in the product system that deliver several outputs or services of which not all are used by the reference flow of the study. According to this hierarchy, the preferred solution is subdivision of the concerned process, and if this is not possible, system expansion and, as a last resort, allocation. Below, examples are given for how to carry out each solution in practice. This guidance is primarily relevant for the foreground system because multifunctionality has typically already been handled for the processes in the LCI databases that are used to construct the background system. Some LCI databases exist in different versions, according to how multifunctionality has been solved (see Sect. 9.3 below). For the background system this reduces the job of the LCA practitioner to just source processes from the appropriate version of the LCI databases. Yet, even in the background system, the LCA practitioner may sometimes have to solve multifunctionality manually when no appropriate solutions exist in the used LCI databases. We note that many waste treatment processes are multifunctional because they both offer the function of managing (often heterogeneous) waste streams and the function of providing product flows, such as recycled materials or electricity. We refer to Chap. 35 on application of LCA to solid waste management systems for more details on how these special cases of multifunctionality are solved in LCA practice.

Subdivision

When possible, subdivision should always be the solution to multifunctionality. Unit processes can be defined at many levels of detail and for the use in LCA there is no point in detailing them beyond what is needed for the modelling purpose in the LCA. This may mean that by increasing the detail applied in the modelling, the multifunctionality may be revealed as artificial. For example, a process that encompasses an entire factory producing two different products may have been identified from the procedure detailed in Sect. 9.2.1. If this factory is in fact using different and independent machines and work stations for manufacturing the two products, the initial process can, by introducing additional detail in the modelling of the process, be subdivided into two or more processes that each contribute to the production of only one of the products, see Fig. 9.2. Note that it is often not possible to fully physically divide a process according to the co-products. In the factory example room lighting, room heating and administration (all level 3 processes, according to Sect. 9.2.1) may not be possible to divide between the co-products. In such cases, subdivision needs to be supplemented with or replaced by another solution to multifunctionality. Note also, that in practice data availability often determines whether subdivision is possible. In the factory example, it may be that data only exist for the electricity consumption of the entire factory, i.e. the consumption of each machine is unknown and in this case, subdivision would be practically impossible. In addition, there are many situations where the creation of the co-products is integrated into the process in a way that impedes the multifunctionality to be addressed by subdivision. This is the case for many biological and chemical processes.

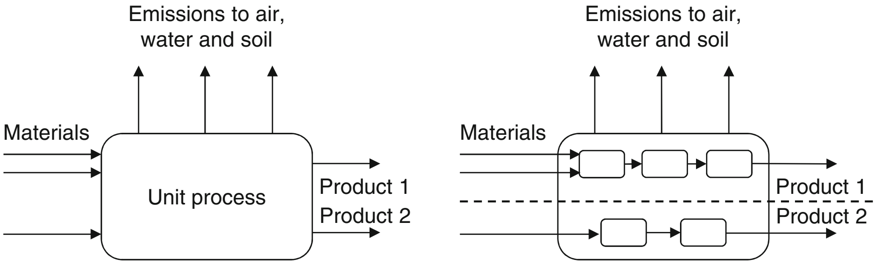


Fig. 9.2 Solving the multifunctionality problem by increasing the modelling resolution and sub-dividing the process into minor units which can unambiguously be assigned to either of the functional outputs

System Expansion

System expansion is second in the ISO hierarchy. As explained in Sect. 8.5.2, system expansion is mathematically identical to crediting the studied product system with the avoided production of the secondary function(s) that would alternatively have been produced and delivered somewhere else in the technosphere. When modelling a life cycle inventory, the technique used to perform crediting varies between LCA software (see Sect. 9.5). The identification of avoided processes depends on the decision context. For Situation A and C1 a market mix is used, which corresponds to the average process used to supply the entire market (see Sect. 8.5.4). To calculate a market mix, one needs to know the amount of product or service that is produced and delivered to the relevant market by each process at the time when the secondary function is delivered by the studied product system (see Fig. 8.13). So, for example, if recycled steel is a co-product of a studied life cycle and the two processes for producing steel, electric arc furnace (EAF) and a basic oxygen furnace (BOF), delivered 60 and 140 million tonnes, respectively, in the relevant market and reference year, then the market mix would be 30% EAF and 70% BOF (World Steel 2015). The LCI model should thus be credited with a constructed process composed of 30% of the flow quantities associated with the production of 1 unit of EAF steel and 70% of the flow quantities associated with the production of 1 unit of BOF steel. It is important to identify the correct market for each system expansion. The correct market must reflect the geographical and temporal scope (see Sect. 8.7). Note that some goods and services are sold in global markets due to the low cost of transportation relative to their value (e.g. gold), while other goods and services are sold on local or regional markets due to high transportation cost (e.g. some biomaterials and water) or regulation. Information on volumes produced and delivered to markets can often be obtained from reports or databases of industry organisations (e.g. the World Steel Association in the example of recycled steel). In consequential modelling (parts of Situation B, see Sect. 8.5.4), the avoided process is not a market mix, but the marginal process (or a mix of marginal processes) and its identification is explained in Sect. 9.2.3.

Allocation

Allocation is the third and last option in the ISO hierarchy. As mentioned in Sect. 8.5.2 allocation should, when possible, be based on (1) causal physical relationship, followed by (2) a common representative physical parameter and, as a last resort, (3) economic value.

The causal physical relationship approach is possible when the ratio between quantities of co-products can be changed. Consider again the above example of a factory producing two products (x and y), where only the total electricity consumption is known. Here it would be possible to derive the electricity consumption of x and y by collecting data on production volumes and total electricity consumption at two points in time, where the relationship between the produced quantities are different. This could lead to the following simple system of equations:

$$\text{Time 1}: \ 10\,\text{tonnes} * X + 20\,\text{tonnes} * Y = 10.000\,\text{kWh} \tag{9.1}$$

$$\text{Time 2}: \ 10\,\text{tonnes} * X + 40\,\text{tonnes} * Y = 12.000\,\text{kWh} \tag{9.2}$$

Here, X and Y represent the electricity consumption of product x and y (kWh/tonne) and by solving the equation system, one finds that X is 800 kWh/tonne and Y is 100 kWh/tonne. If time 1 is representative for the unit process to be applied in the LCI model, then 80% (10 tonnes * 800 kWh/tonne divided by 10.000 kWh) of the factory's electricity consumption should be allocated to product x. Note that this 80% allocation factor should not blindly be applied to allocate the remaining flows (e.g. consumption of heat and emissions of NO_x) between product x and y, for which the causal physical relationships may be different. Note also that allocation according to a causal physical relationship is in many cases not possible, because the ratio between co-products or co-services for many processes cannot be changed. For example, it is not for practical purposes possible to reduce or increase the production of straw, while keeping the production of wheat constant.

The representative physical parameter approach is possible when co-products provide a similar function. For example, in the case of a fractional distillation process of crude oil, a similar function of many of the co-products (e.g. diesel, petrol, kerosene, propane and bunker oil) is to serve as a fuel to drive a process performing mechanical work, and therefore exergy, which can be interpreted as the maximum useful work, is an appropriate representative physical parameter. The parameter values of each co-product can typically be obtained from physical or chemical compendiums (e.g. in the case of exergy values). Once the values have been obtained, calculating the allocation factor is straightforward. For example, if co-products x, y and z are produced in quantities 1, 3 and 6 kg and if their representative physical parameter values are 10, 1, and 0.5 per kg, then the total parameter value would be 16 i.e. (1 * 10 + 3 * 1 + 6 * 0.5) and the allocation factor for product x would be 62.5% (1 * 10 divided by 16) and so on. Note that in the distillation process case, the functions of the co-products are not entirely identical. Airplanes cannot fly on bunker oil, and bitumen, one of the co-products, cannot be used as a fuel. Allocating according to a representative physical parameter is therefore not ideal, but may be the best solution, compared to other allocation approaches. This example illustrates that there is often not a single correct allocation approach and the choice of approach therefore depends on the judgement of the LCA practitioner. The sensitivity of the LCA results to this judgement may be investigated in a sensitivity analysis applying different possible allocation factors, as explained in Sect. 9.6. Note that it is very important to choose a representative parameter that is actually representative for the function of all co-products. For example, mass is not a representative parameter for the co-production of milk and meat from dairy cows because the functions of milk and meat are not their mass. In this case, some measure of nutritional value would be a more representative parameter.

The economic value approach is recommended as a last resort and is generally easy to carry out due to the abundance of price data on goods and services. Prices may be obtained by contacting the company running the multifunctional process in question or from the stock exchange in case of global markets, e.g. for some metals. For some co-products there may not be a market because they need to go through additional processing before they are sold. In that case, the LCA practitioner should calculate a shadow price. For example, straw, a co-product of wheat production, needs to be baled before it is sold, and the economic value of baled straw must therefore be subtracted the cost to the farmer of baling the straw to calculate the shadow price of the unbaled straw leaving the multifunctional process of wheat production. Note that the prices of most goods and services are volatile to varying degrees. It is therefore recommended to calculate average values for the time period that is relevant to the temporal scope of the study (see Sect. 8.7.2). Once the economic values have been determined, allocation factors are calculated in the same way as the above generic example for the representative physical parameter approach.

It should be noted that although allocation by economic value is the last resort according to ISO, it is widely used in practice. This is because the other solutions to the handling of multifunctional processes are often not possible due to the nature of the multifunctional process or due to lack of the required information and data to identify the relevant process for a system expansion or to determine a causal physical relationship, or a common representative physical parameter. By contrast, the price data needed to carry out economic allocation is generally available. For this reason, economic allocation is done by some LCA researchers recommended as a default solution to multifunctionality, e.g. by the Dutch CML Guideline (Guinée et al. 2002), and the LCI database ecoinvent comes in a version where allocation by economic value is systematically applied to all multifunctional processes (see Sect. 9.3.2 below).

9.2.3 Consequential Modelling

In most cases, a consequential LCI will include other processes than an attributional LCI for the same product system. The attributional LCI includes the processes which the assessed product 'sees' from its journey from the cradle to the grave. If, for example, the assessed product is a plastic cup, the start of the journey will be some extracted crude oil, which through a sequence of production processes will be processed into plastic. This will then be transported to the shop, be bought by a user, who will use it once and then discard it, after which it will be transported to, say, an incinerator and burned. In the attributional LCI, each of these processes: the production of crude oil, the conversion into plastic, the transport and incineration will be included.

The consequential LCI is different; the goal of the assessment is to identify the environmental impacts caused by a decision, for example the decision to buy a plastic cup. The processes that change due to a decision may not be the same that a product 'sees' throughout its product life (see Fig. 9.1). The following example may make this easier to understand.

Assume now for the sake of the example that we have reached the peak in oil production: we simply cannot economically extract more oil than we are already doing. This implies that the decision to, say, use this plastic cup will not result in an increase in the production of oil, as this is already at its maximum. What happens instead may be that the price of oil will go up due to the increase in demand (which in this example is going to be extremely small due to the small amount of oil needed to produce the cup. However, here it is the principle that is of interest). The increase in price may cause other users of oil to reduce their use, or find a substitute for their use of oil. In this example we will assume that some oil users will find natural gas a suitable substitute and these users will therefore increase their demand for natural gas to compensate for the decreased availability of oil. This implies that, given these assumptions, an increase in the demand for oil created from the increase in demand for plastic cups will not result in an increase in the production of oil, but rather in the production of natural gas. The consequential LCI will therefore not include an extraction of oil, but rather an increased extraction of natural gas. This line of thinking obviously does not only relate to the oil used in the production of the plastic, but to all the inputs used when the plastic cup is produced.

Another very important difference between the attributional and consequential LCI is that in an attributional LCI the normal procedure is to assume that the electricity consumed in the production of the plastic cup is produced by all the suppliers on the market, depending on their market share. In a consequential LCI, this is different: If we increase the demand for electricity in the market, it is most likely that not all the suppliers are going to increase their production to meet the increase in demand. The reason is that the most cost-efficient producers will already produce at full capacity. This is for example going to be the case for nuclear power plants. This means that if we increase the demand for electricity, we will not influence the extent of the production from the nuclear power plants. Rather, we will influence other types of power plants, for example natural gas power plants, which are more expensive to operate (per kWh), and which will therefore only produce during peak load situations (when electricity prices are higher). The same thinking is applied when studying the effect of increasing or decreasing demands for other products than electricity. Rather than including an average of the producers in the market in the LCI, as is done in the attributional LCI, it is the 'marginal' producers, which are included in the consequential LCI. A marginal producer is a producer who will change its supply due to small changes in demand.

A final important difference between the attributional and consequential LCI lies in the handling of multifunctional processes (see Sect. 8.5.2). In a consequential LCI, the multi-output processes are always handled by system expansion (if subdivision is not possible).

Based on the outline above, there are generally three different tasks in a consequential LCI:

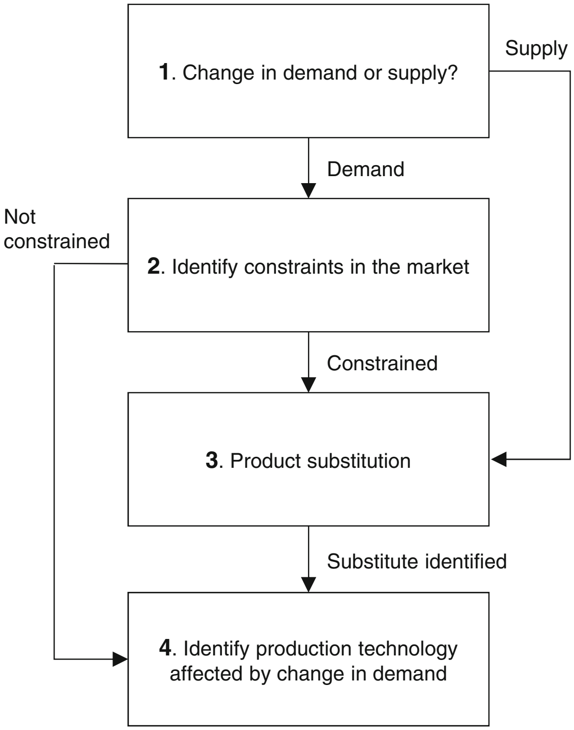
1. To identify whether an increase or decrease in demand for a product will actually lead to corresponding increases or decreases in supply for that product. As illustrated with the oil and gas example above, this is not necessarily the case.
2. To identify which production technology will be affected by the change in supply of products. This is most likely not going to be an average of the production technologies on the market, but rather one or a few operating on the margin.
3. To identify which product substitutes which. This is relevant when changing demands for a product whose production is constrained, such as oil in the example above. It is also relevant for the handling of multi-output processes, where it involves identifying the product that will be affected (substitute or be substituted) by a co-product from a multi-output process.

From the discussion above, it can be seen that if we want to perform an attributional LCI, we can do so simply on the basis of knowledge about the product and the parts that it includes: we need to know about how plastic cups are made, used and discarded. However, if we want to perform a consequential LCI, besides the technical knowledge about how the plastic cup is produced, used and discarded, we also need knowledge about how the market reacts to an increase (or decrease) in demand and supply.

As can be imagined, answering how the market reacts is easier said than done. What will actually happen if I increase the demand for this or that? Modelling the reactions of the market is a very complex task—just ask any stockbroker! Outlining what will happen is therefore necessarily somewhat uncertain, especially if the assessment addresses decisions in the more distant future. However, to ease the answering of these questions we will in this chapter outline a range of 'rules of thumb' developed for identifying the processes that are likely to change due to a decision.

As outlined above, the goal of the consequential LCA is to answer questions of the type: *"What are the environmental consequences if ...?"*. As the environmental consequences that are considered arise from changes in production of products, this overall question answered in the consequential LCA can basically be translated to "What changes in the production of goods if we demand/supply more/less of X($, Y$, Z, …)?". We continue asking this question until we have covered all induced changes. For example, in the case where we want to assess what happens if we use a plastic cup, we basically want to increase the demand for plastic cups. We therefore start by asking: *"What will happen if I increase the demand for plastic cups?"* If what happens most likely turns out to be that additional cups will be produced, then the follow-up question will be: *"What will happen if we produce additional plastic cups?"* The overall approach of identifying processes to include in a consequential modelling of the product system is to repeatedly ask this question for each step upstream and downstream from the reference flow (see Sect. 9.2.1) until all changes have been covered.

Fig. 9.3 4-Step approach for identifying affected process in a full consequential LCA



We recommend solving this task by following a 4-step procedure shown in Fig. 9.3. Depending on the concrete case, one or more steps can be skipped (as will be explained below).

Step 1: Change in demand or supply?

When performing a consequential LCI, full elasticity of supply is generally assumed. This implies that a change in demand for some function will lead to a change in supply of products that can fulfil this demand, but that change in supply, will not lead to a change in demand. There will therefore be a difference between the market effects of changing demand and changing supply, as will be visible in the steps below.

First step in the procedure is therefore to consider whether the question at hand addresses a change in demand or supply; e.g. are we assessing the question: “What happens if I *demand* more/less of *X*?” or the question “What happens if I *supply* more/less of *Y*?” Note that handling a co-product from a multi-output process in the studied life cycle relates to changes in supply of this co-product, and therefore is related to the latter type of question.

If the assessed decision relates to changes in demand, go to Step 2. If it relates to changes in supply, go to Step 3.

Step 2: Identify constraints in the market

If we increase (or decrease) our demand for *X*, the market will, according to standard economic theory, respond by increasing (or decreasing) the supply of *X*. In many cases, at least on a short term, there will not be a one-to-one relationship between increases in demand and supply. The reason is that an increase in demand will often result in an increase in price, implying that some users may stop using the product and potentially find a cheaper substitute product. Hereby, the supply and demand will reach a new steady state, which will often not entirely correspond to the initial demand plus the increase. Despite that these thoughts about price elasticity have been introduced in LCA literature, for simplicity, the default assumption here will be that the increase (or decrease) in demand will spur an equally large increase (or decrease) in supply, which is also the most common assumption in consequential LCI.

However, in many cases markets face various constraints and other market imperfections. An increase (or decrease) in demand will therefore not always lead to an increase (or decrease) in supply. Market limitations may be of a legal, economical, technical or physical nature. For example, straw used for co-firing in power plants is, due to the transport cost to value ratio, not transported far from the production site. Moreover, as there is limited production capacity of straw in a given area, an increase in demand within this area will in many cases not result in an increase in supply. Another example may be the demand for recycled metals, which are often constrained by the amount of waste input to recycling processes, in which case an increase in demand will not result in an increase in supply of recycled metals. Other constraints may be due to legally set boundaries for how much of a certain good may be produced. If the production already fills the boundaries, a small increase or decrease in demand will also not have any effect on supply.

There are thus a number of situations where the default assumption—that an increase or decrease in demand results in an increase or decrease in supply—may not hold true. In these situations, *the market is constrained*, and a central task will be to identify how existing or potential users will handle the increase or decrease in demand. In the example above with an increased demand for recycled metal, a reasonable assumption may be that existing users of the recycled metal will use virgin metal instead. In other words, an increase in the demand for a product already produced at maximum will not lead to an increase in supply, but more likely make existing users find a substitute. A guideline for identification of which products can substitute which is provided under Step 3.

The assessed decision may also lead to a decrease in the demand for a product, which is only produced to a certain amount. If this product is already fully utilised, a reasonable assumption may be that a decrease in demand for the product in question will not lead to a decrease in the supply of this product, as other users will use up the freed supply. In the metal example above, this could imply that the freed supply of recycled metal will be used up by a user of virgin metal, in total lowering the demand of virgin metal, while keeping the utilisation of recycled metal at the same level.

It may also happen that the freed supply resulting from a decreased demand does not lead other users to utilise the product. If this is the case, it can be assumed that less will be produced of the product, or if the product is a co-product of another and more valuable product, and its production therefore bound, it may end up as waste, implying that a decrease in the demand for the product will simply imply more waste.

It may seem an enormous task to try to identify whether all the commodities included in the life cycle are constrained in their production. However, in practice the assumption will often be that a product is constrained if:

- It is a co-product from a process that has another more valuable product, as it will never be the less valuable product that will control the overall output of the production (e.g. waste from a slaughterhouse that may be utilised for biodiesel production is constrained by the amount of meat produced).
- Its production is limited by regulation (e.g. regulation may set a limit for the overall annual catch of commercial fish species).
- Its production is limited physically (for example the production of wood on an island is restricted by e.g. forest area and a high cost of transportation may mean that import is not an economic option).

Identifying whether a commodity is produced as a less valuable by-product will often be quite easy, but the identification of both regulatory and physical constraints may be more difficult. It will in many cases require knowledge about the specific market in which the change in demand is made, which will often require advice from experts. Furthermore, one must know whether the production capacity for the product, for which demand is changed, is already filly utilised. Figure 9.4 presents a decision tree for dealing with potential market constraints.

In case of unconstrained markets, go directly to Step 4. Constrained markets must in some cases (see Fig. 9.4) be studied in Step 3 first to identify what other users prefer as a substitute (in the case of increased demand) or which substitute other users stop using (in the case of decreased demand).

Step 3: Product substitution

As noted in Step 1 it is commonly assumed in consequential LCA that supply follows demand. This implies that if we change supply, we will not change the demand but rather affect the competition between suppliers to cover the demand. For example, if we reduce the supply of crude oil on the market, it is assumed that the crude oil users will attempt to find a substitute for the crude oil, creating a demand for other products satisfying the same service as offered by the crude oil. The demand for the service that the crude oil is providing is thereby assumed to be constant, but there is a change in the way the demand is met.

Following this assumption about demand driven consumption, changes in how the demand is met may arise if the supply of a product is changed, or if we change demand for a product whose production is constrained (as explained in Step 2).

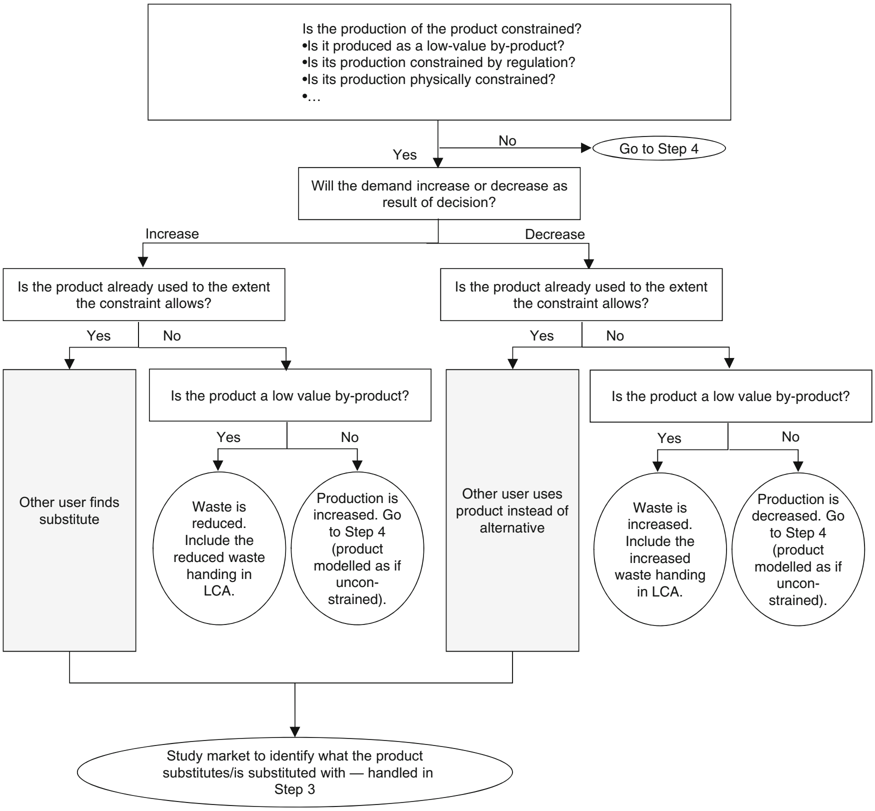


Fig. 9.4 How to identify constrained production and how to handle it

In each of these cases, we need to identify the substitutions that occur in the market, like in the above example where gas substitutes oil. The question that we will address in this step of the consequential LCI is: *"How do we identify which product substitutes which?"*

In order to identify which products can substitute which, there are two aspects that we have to consider:

- The products must deliver the same service(s) for the product user.
- The product working as a substitute has to be available.

Below we will address each of these two issues.

Identifying a satisfying substitute for the product user

A product may provide different services for different users, implying that one product may be a fully satisfying substitute for one user, but completely useless for another. Thus, to identify which product can substitute which, we first need to identify the product user who is likely to find a substitute due to an increase in demand or decrease in supply or who decides to use the product instead of a substitute due to a decrease in demand or increase in supply, i.e. *the marginal user*. However, in reality, identifying the marginal user may be very difficult. Therefore, if a market analysis shows that the product is used in significant amounts for several different purposes, it is advised to make different scenarios for each of these potential substitutions. This can feed into sensitivity and uncertainty analysis of an LCA (see Sect. 9.6 and Chap. 11). In this case, this step should be followed for each of the scenarios.

Having identified the marginal product users and what they use the product for, the next step is to identify what can be used as a substitute for the product by the different marginal users.

Identifying what will be a satisfying substitute for a specific user will in most cases require a large amount of background information about the market where the substitution will take place, and hence involve some elements of uncertainty. However, for a product to work as a substitute, it needs to fulfil the same functions for the user. As outlined in Weidema (2003), these may relate to:

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

Apart from the basic functionality of the product, which can be seen as an obligatory property of the product (see Chap. 8), the importance of these properties will to a large extent depend on the product user. If the product user is a company using the product in its production, the functionality and technical quality will normally be the most important, for some companies accompanied by health and environmental issues. For consumers, on the other hand, issues like aesthetics and image may have a high priority.

It should be noted that there may be not one but several products that work as a substitute for a product. If it is possible to identify the distribution between the alternative product substitutes, the consequential LCI should be based on this. If this is not possible, it may be necessary to develop several scenarios for each of the likely substitutes.

Product availability

Ensuring that the substitute has the necessary functionality, however, is not enough. The substitute also has to be available. A substitute is unavailable if constrained and already used to the extent that the constraint allows. To identify whether the substitute is available, we need to perform parts of Step 2 (included in the decision tree below), which also had as a goal to identify the availability of a product. As the discussion of how to perform this identification is going to be the same as under Step 2, the reader is referred to this section for further explanation.

Figure 9.5 presents a decision tree for identifying product substitutes.

As an additional consideration, it should be noted that in some cases one product will not substitute another directly. For example, the production of biodiesel leads to the co-production of glycerol which contains salts and other impurities. Before it

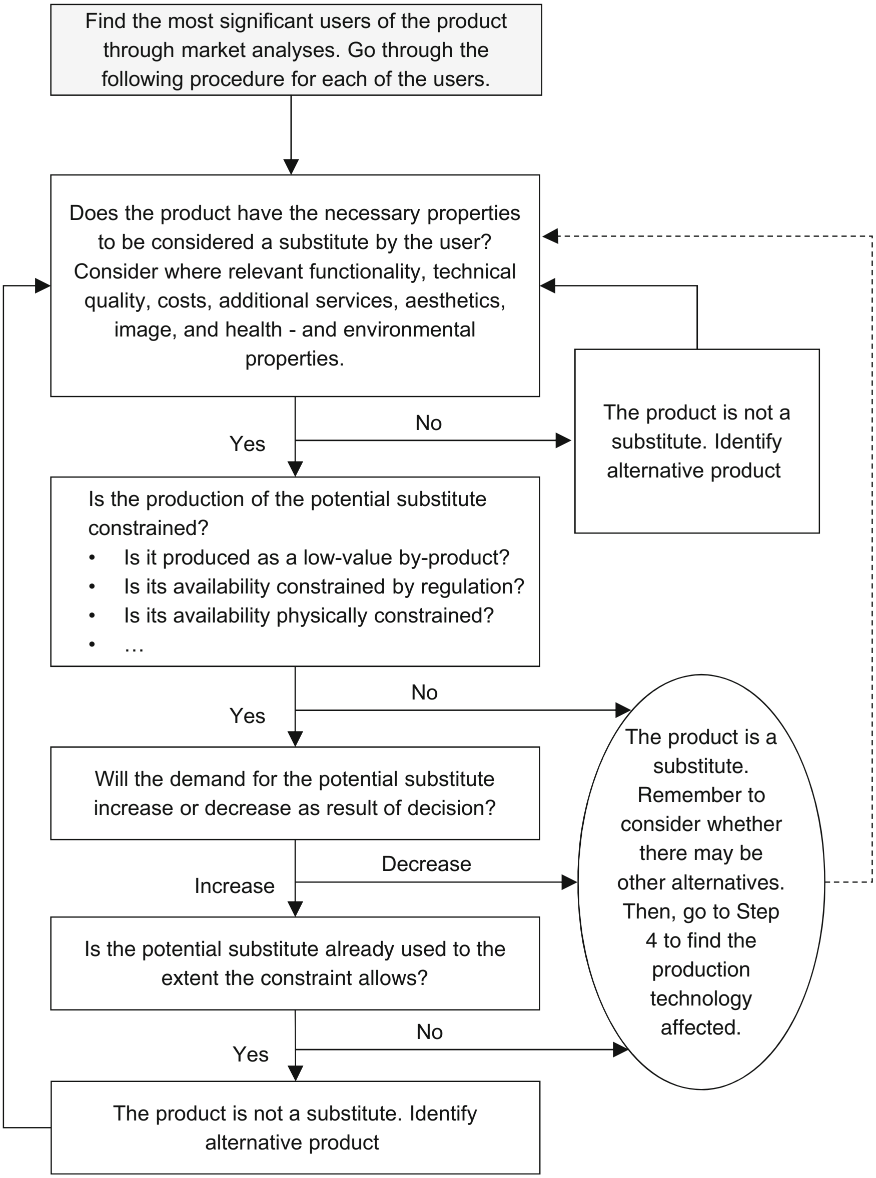


Fig. 9.5 Procedure for identifying possible substitutions of products as consequence of changes in supply or demand

can be sold on the glycerol market, it therefore needs to be distilled. In this case, and in others where additional treatment is needed for the product to be considered as a substitute, these additional treatments need to be included in the LCI. Also, it should be noted that in some cases a product substitution may create a cascading substitution effect (not captured by Fig. 9.5 for simplicity). E.g. if a decrease in demand for product A leads to other users using product A instead of B (substitutes), which is a waste product that is fully used (nothing goes directly to waste management), this can lead to other users using product B instead of C (substitutes), and so on and so forth.

Step 4: Identify production technology affected by change in demand

If the product for which the demand is changed is not limited in supply, it will normally be assumed in a consequential LCI that supply follows demand in a one-to-one relationship. The question is, however, which production technology will be affected by the change in demand. Identifying this technology is the purpose of this step.

In many cases, similar products can be produced with very different environmental impacts. Just think of electricity that may be produced from wind turbines or coal fired power plants. It is therefore in many cases important to identify not only that the production of a certain product will change as a result of the assessed decision, but also to identify as accurately as possible which supplier, and hereby which production technology will be affected by the change in demand.

For doing so, three issues need consideration: The size of the change in demand created by the decision, the trend in the market and whether the assessed decision leads to an increase or a decrease in demand. These issues will be discussed below.

Size of change

When identifying which technology will be affected by the change in demand, it is important to distinguish two different perspectives: The immediate production perspective and the perspective relating to changes in production technologies in the market. Consider the following example of electricity generation: Some technologies cost more to run than others. The production of electricity from gas turbines is, for example, often more expensive than electricity produced from coal. This implies that only coal power will be used, when the capacity of the installed coal power plants is sufficient to cover the demand. However, when the demand increases above what can be supplied by the coal power plants, gas power plants will start to produce. From an immediate production perspective, the concrete technology that will supply the demand will depend on the cost efficiency of the production technologies with available production capacity—the least cost efficient will be only be used to supply peak load.

However, this is only the immediate consequence of the decision. If the electricity consumption in the given market in general is increasing or stable, a decision leading to an increase in demand will push for an increase in the installed power production capacity. In other words, the decision will have an effect on installed capacity. Assume now that the planned implementations of power plants in the market are wind turbines. The long-term effects of increasing the demand will then be a corresponding increased implementation of wind turbines.

The difference between the immediately affected production technology, known as the 'short-term marginal' and the effect on the installed production technology, known as the 'long-term marginal' may be very large—in the example above, the difference was between coal and gas power and wind. It can therefore be a very important decision for the results of the LCA whether the short or long-term marginal is used in the LCI. The general rule has been to use the long-term marginal when the assessed decision is creating large changes in demand, and use short-term marginal when the assessed decision creates small changes in demand. A change in demand is in this context considered small, if it is smaller than the average percentage of annual replacement of capacity (often around 5%, see below). The argument is that these small changes will be part of the general trend in the market and therefore be handled by the trend in the market. The signal they send is therefore considered too small to overcome the threshold for a structural change in production capacity. The difference in the size of changes assumed in the LCA is in fact what makes Situation A and B studies different in the ILCD classification (see Sect. 7.4).

Trend in the market

The electricity example above relates to the situation where the market trend points towards a stable or increasing demand. However, if the market trend is rapidly decreasing, the long-term marginal response to a decision that leads to an increase in demand will not be an increase in the implementation of more wind turbines but rather the continued use of coal or gas power plants that would otherwise have been taken out of operation. In this market, the demand caused by the assessed decision will thereby make the existing least competitive technology stay longer on the market.

The distinction between whether the trend in a decreasing market is slowly decreasing or rapidly decreasing depends on whether the decrease happens below or above the average replacement rate for the production technology. For example, a market trend would be characterised as rapidly decreasing if it decreases by 10% per year, while the average replacement rate for the production technology is 5%. Note that a replacement rate of 5% means that production plants are designed to operate for 20 years, which is quite common, depending on the technologies involved. The reason for making this distinction in market trends is that for increasing, stable or slowly decreasing market trends there is a need for implementation of new production technology, and changes in demand will therefore affect this implementation rate. For rapidly decreasing market trends, however, the decrease is faster than the decommissioning rate for the technology, implying that production plants would be taken out of use before their design life time. In such cases (small) changes in demand will not lead to changes in implementation of new technology (e.g. wind turbines), but merely to the changes in the speed of decommissioning (e.g. coal or gas power plants).

Increase or decrease in demand

The electricity generation example above relates to the situation where the assessed decision leads to an *increase in demand*, and the general trend in the market is either on the increase or decrease. However, the assessed decision may also lead to a *decrease in demand*. If the assessed decision leads to a large decrease in demand in a market with an increasing market trend, the implementation of new technologies will be postponed, implying that existing least cost effective technologies will continue to be used for a longer time.

As showed in the discussions above, there are three aspects that need to be considered, and since each of them has two possible outcomes, there is a total of eight possible combinations. Not all combinations were discussed above, but they follow the same logic. Table 9.1 summarises the discussions above and gives an outline of how to perform the identification of which technology is affected by a change in demand for all eight combinations.

Table 9.1 Identification of the technology which will be affected by a change in demand (i.e. the marginal technology)

	Long-term marginal	Short-term marginal
Decision leads to *increase* in demand	*Increasing* market trend: Implementation of new production technology is promoted—increase in demand is supplied by the production technology *to be implemented* in the context	*Increasing* market trend: Less cost-efficient technology will be used to supply increase in demand—increase in demand is supplied by *least* cost effective technology available on the market
Decision leads to *increase* in demand	*Decreasing* market trend: Decommissioning of least competitive technology is delayed. Increase in demand is supplied by *least* cost effective technology available on the market	*Decreasing* market trend: Less cost-efficient technology will be used to supply increase in demand. Increase in demand is supplied by *least* cost effective technology available on the market
Decision leads to *decrease* in demand	*Increasing* market trend: Implementation of new production technology is delayed. Decrease in demand saves the supply from production technology *to be implemented* in the context	*Increasing* market trend: The least cost-efficient technology is no longer needed because of reduced demand. Decrease in demand saves the supply from *least* cost effective technology available on the market
Decision leads to *decrease* in demand	*Decreasing* market trend: Decommissioning of least competitive technology is promoted—decrease in demand saves the supply from *least* cost effective technology available on the market	*Decreasing* market trend: The least cost-efficient technology is no longer needed because of reduced demand—decrease in demand saves the supply from *least* cost effective technology available on the market

After identifying the production technology affected by the change in demand, go to Step 1 again to address other changes created by the assessed decision, if all changes are not already handled.

The table shows that, depending on the combination of the three aspects, the marginal technology can either be the least cost effective technology available on the existing market (6 of the combinations) or the future production technology to be implemented (2 of the combinations). In practice, the marginal technology, especially long term, can be difficult to identify, and this is a potential source of considerable uncertainty in the inventory analysis. The importance of this uncertainty may be investigated by sensitivity scenarios for the different potential marginal technologies. Furthermore, it is possible to create a mix of potential marginal processes, which means that the inventory data becomes a mix of data from the different potential marginal processes, as demonstrated in Sect. 9.5. This approach is used in the ecoinvent database in its version 3 (and higher).

Note that in the discussions above, we have mentioned 'the market' as one entity. However, in reality, there may be many markets for one product, e.g. when the product has high transportation costs compared to the value of the product. In cases where there are many small markets for the same product, the market trend has to be identified in the affected local market. For other products where the transportation costs are lower, there may be only one global market. The spatial nature of a market has to be established as a first task when identifying changes in supply.

Secondary consequences and concluding remarks

In the presented 4-step guidance we have only addressed the rather 'direct consequences' of increased or decreased demands and supplies. However, several derived effects or secondary consequences of these direct consequences may be found. Depending on the size of these consequences and the scope of the assessment, these may be relevant to consider. Common for each of them is that they are difficult to foresee and even more difficult to quantify. We therefore cannot establish a general procedure for identifying and quantifying these, more than stating that in-depth knowledge on the topic of concern in most cases will be necessary. A few examples of the types of secondary consequences are given below.

Additional or reduced production of a product may affect market prices for the product hereby affecting the broader demand for the product. For example, if the assessed decision will lead to the increase in the cost of, say, wheat, the behaviour of other consumers may be to consume less wheat due to this increase. It may also be that due to the increase in price, some consumers will begin to use, e.g. corn instead of wheat, hereby increasing the demand for corn.

Changes in market prices may not only affect the consumers but also the producers. In the example above, increases in wheat prices may cause producers to increase the intensity of their production, typically done through increasing the fertiliser use, or through increasing the agricultural area (for more discussions about secondary consequences specifically related to biomaterial production, see Chap. 30). However, it may also be imagined that the increase in price of wheat may cause producers to intensify research related to yield increase, potentially leading to, say, a decrease in area/fertiliser/pesticide use per produced unit of wheat.

Other types of ‘secondary consequences’ related not to prices of products but to the time consumption of products can also be imagined for some products. For example, a washing machine may lead to significant time savings for the user. The question is then what this time will be used for. In some cases, what is gained in terms of time savings by various household appliances is to some extent used on other ‘time-consuming’ household appliances, such as TV or videogames. When assessing a washing machine, it may therefore in some cases make sense to include an increase in power consumption from the TV set, or something similar.

As may be obvious from the example above, identifying the secondary consequences will in many cases be very difficult and associated with considerable uncertainties. Furthermore, these effects are typically far from linear and when certain thresholds are passed a complete shift of parts of the market can be the consequence (e.g. the point where the production cost of wind power makes it fully competitive in certain market segments).

Whenever these effects are considered in an LCA, it will often be advisable to make several different scenarios where various realistic possibilities are addressed in order to assess the potential variability of the results (see Sect. 9.6).

However, despite the problems of identifying these secondary consequences, it is evident that if the goal of the assessment is to get as complete an overview of the consequences of a decision, none of these should be omitted a priori, but should be included if at all considered to be practically possible and important for the outcome of the study.

This concludes the introduction and guide to consequential LCA. Readers are invited to consult the Appendix for an example of how to use the 4-step guideline in a case study of the consequences of increasing the supply of biodiesel from poultry fat. As we hope to have demonstrated, consequential LCA is conceptually appealing because it aims to address the consequences of a potential decision. After all, why bother making an LCA study (or paying for one) if its outcomes are not expected to have a consequence on the physical world? We also hope to have demonstrated that the answers to the many questions that need to be addressed throughout the 4-step guide are often associated with large uncertainties. Even advanced economic models generally do a poor job at predicting concrete consequences in markets following some sort of perturbation (consider how global financial crises tend to take also financial analysts by surprise) and simplifying assumptions have to be applied. These uncertainties are one reason why many LCA practitioners prefer an attributional approach. Its use of average process data and frequent use of allocation is theoretically difficult to defend when the goal of an LCA study is to support decisions (i.e. study the consequence of decisions), which is the case for Situation A and B studies in the terminology of ILCD (see Sect. 7.4). Yet, attributional LCA does not suffer from uncertainties related to economic modelling and is preferred by some LCA practitioners for this reason and considered to be ‘on average more correct than consequential LCA’. This is also part of the reason why ILCD recommends an attributional approach even for goal situation

A where the LCA supports a decision but the scale is small and market elasticities make identification of the marginal product or technology uncertain in many cases.

9.3 Planning and Collection of Data

Based on the scope definition and the processes identified to belong within the system boundaries, the collection of data for these processes has to be planned and carried out. The planning has the purpose of balancing the effort of data collection by the relevance of the respective data and information. This is essential in order to avoid wasting time on collecting high-quality data that have a low relevance for the LCA results and/or spend too little time on collecting high-quality data where it is highly relevant for the results. Planning and collection of data are iterative processes, which is why they are addressed together in this section. These processes are an integrated part of the iterative approach to LCA that also involves the calculation of LCIA results. For example, the first iteration of LCIA results may guide the practitioner about which data are particularly relevant to focus on in a second iteration.

As starting point for data collection, we encourage practitioners to create a table that outlines a plan for the data collection for each process or single data point, see template in Table 9.2 (elements of the table are explained below). Note that the data eventually collected by the practitioner will often diverge from the initial plan due to unforeseen limitations and results of early iterations of LCIA phase that may lead to changes in the data specificity that the practitioner aims at for each individual process or single data point. The table can therefore be adapted accordingly at each iteration and be used in its final version (i.e. final iteration of the study) to document the metadata behind the LCI data (see Sect. 9.7).

The initial planning should be based on the requirements to data representativeness from the scope definition, as well as on the efforts that are expected in order

Table 9.2 Template for planning and collection of data

Process or single data point	Specificity					Type	Source	Access
	Very high	High	Medium	Low	Very low			
X	X					Concentration	Process engineer	Questionnaire
Y		X				Kg/year	Academic paper	Online search
Z				X		Unit process	ecoinvent	Database search

The structure of the table can follow life cycle stages of the product. Based on Wenzel et al. (1997)

to obtain data of a given quality. Data quality is here classified into one of five categories of data specificity shown in Table 9.3.

The efforts required to obtain data of a given quality can be estimated for each data point (e.g. a flow quantity) by considering three additional dimensions of the data in Table 9.2: data type, data source and data access. Examples are given for each of these in Table 9.4. The following sub-sections are structured according to the collection of data for each of the five data specificity levels and address challenges that the LCA practitioner commonly faces for each of the three dimensions of Table 9.4.

Table 9.3 Classification of data specificity (inspired by Wenzel et al. 1997)

Data specificity	Explanation
Very high	Measured directly at specific process site or scaled from measurement
High	Derived from measurements at specific process site via modelling
Medium	LCI database process or data from literature specific to actual process, e.g. according to best available technology standard or country average. Specificity may be improved by modifying a process with site-specific data
Low	Generic LCI database process or data from literature, e.g. covering a mix of technologies in a country or region
Very low	Judgement by expert or LCA practitioner

Table 9.4 Three dimensions influencing the effort required to obtain data

		Examples and notes
Data type	Complete unit process	Includes all flows scaled to 1 unit of reference flow for process
	Individual flow to/from process per unit of time	*X* kg/year, covers elementary flows and other flow types
	Technical or geographic parameters	Process pressure, temperature, soil pH, precipitation
	Concentrations	*X* g/m^3 flue gas or waste water to treatment
	Quantities of products bought per year	*X* kg steel of specified grade (i.e. material flow to process)
	Use characteristics	Temperature of clothes washing, driving pattern of car
	Sector statistics	Sector-average data
	Economy-wide statistics	Infrastructure data, trade data
Data source	*Experts internal to commissioner*	
	Process engineers	Flow data on internal processes
	Purchasing department	Supplier data
	Research and development or design	Data on product concepts, not yet marketed
	Experts external to commissioner	
	Researchers	Expert in relevant technological domain

(continued)

Table 9.4 (continued)

		Examples and notes
	Consultants	Person having long experience with conducting similar studies
	Industry representatives	Person with broad overview of relevant industry
	Public	
	Other LCA studies	Academic literature, reports commissioned by companies
	LCI databases	ecoinvent, LCAfood
	LCI models	PestLCI
	Company CSR reports	Mentioning of key environmental figures
	Industry association reports and databases	Volumes produced, average elementary flows
	Legal documents	Details on best available technologies, regulatory thresholds
	National or supranational statistical agencies	Mixes of waste treatment, transport, energy, etc.
	Consumer organisations	Average life time of products
Data access	Online search	Google, databases, websites
	Questionnaire	Employees at commissioning company or suppliers
	Direct dialogue	Physical visits to site, email or telephone contact
	First-hand gathering by LCA practitioner	Measurements at site with own equipment

The points listed under each dimension are illustrative and not exhaustive

9.3.1 Very High and High Data Specificity

The data type to be prioritised is always complete unit processes, because these form the basis of the LCI results. However, for very high and high data specificity, complete site-specific unit processes often do not exist and therefore must be constructed by the practitioner from single data points.

For very high specificity, these data points are directly measured input and output flows, i.e. elementary flows from/to the ecosphere and other flows from/to other processes in the technosphere. Ideally, elementary flow data should be gathered in the physical unit matching the characterisation factors to be applied in LCIA (usually 'kg') per specific reference flow of the unit process (usually the primary product output). For a CO_2 emission (i.e. elementary flow) from an electricity generation process, this would mean an amount of kg CO_2 per kWh electricity produced. Often, a directly measured flow will not be available in this form, but rather as a quantity per unit of time (e.g. kg per year). In this case, the flow needs to be scaled to one unit of reference flow. Figure 9.6 shows an example of how to do this in practice.

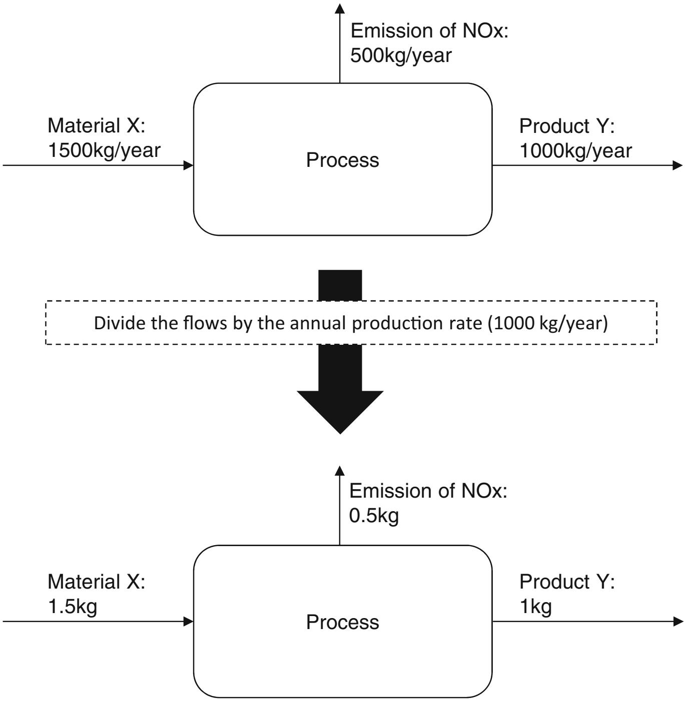


Fig. 9.6 Example of the scaling of three annual flows to one unit (kg) of reference flow (product *Y*)

Often, a company will not possess all the relevant data required for a unit process, due to the cost of systematically measuring all inputs and outputs. When direct site measurements of flows are not available, the flows can be modelled from other site-specific data, in which case the data quality is high, as opposed to very high. Such other site-specific data can be the concentration of pollutants in effluents (typically wastewater or flue gas). Figure 9.7 shows an example of how to calculate copper emissions to untreated wastewater from the concentration of copper in the wastewater.

Another approach is to calculate output flows from site-specific measurements of input flows using a mass balance. Since unit processes, in general, do not gain or loose mass (or energy) over time, the mass of inputs should equal the mass of outputs. So, if a company consumes 10 m^3 of natural gas per year, the CO_2 emissions can be estimated from the mass of natural gas (calculated using its density) and the stoichiometry of the combustion reaction (natural gas is mainly composed of methane, CH_4). A mass balance approach can also be applied to modelling at the level of elements. If for example, a company consumes 950 g copper per unit of reference flow, but one unit of reference flow only contains 928 g copper, then the remaining 22 g per unit of reference flow must leave the process as

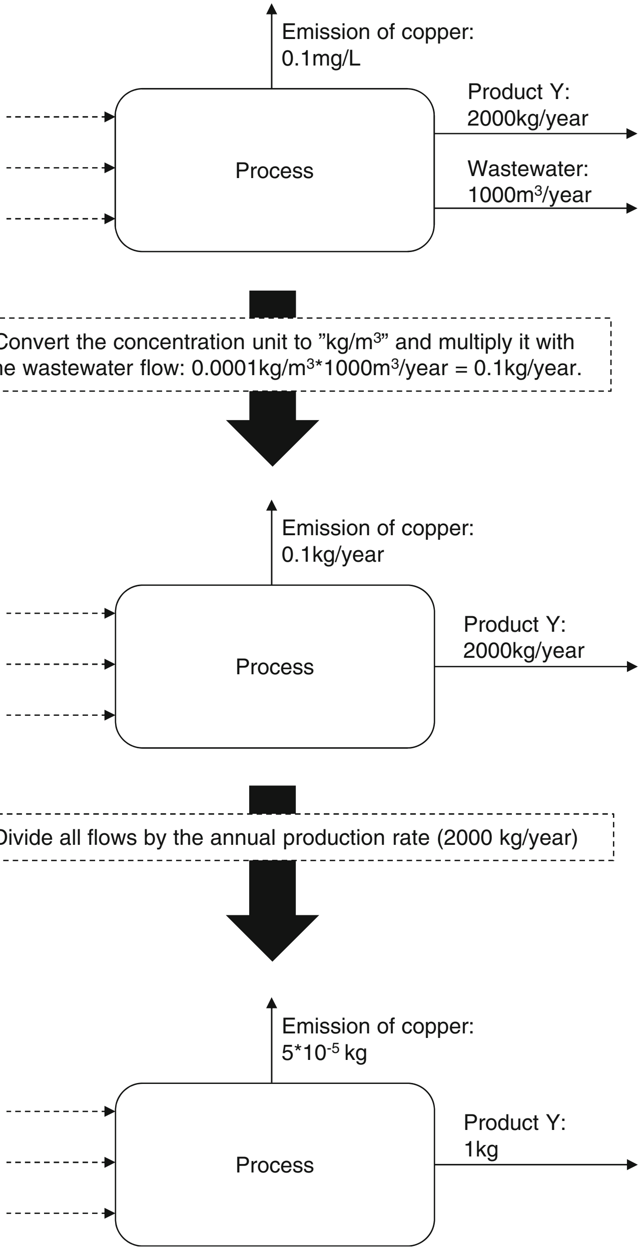


Fig. 9.7 Example of the calculation of an emission per reference flow (1 kg of product *Y*) from a wastewater concentration. *Dotted arrows* indicate input flows not considered in the example

a waste flow to treatment or as an emission. In many cases, a simple back-of-the-envelope mass balance calculation will not suffice, because the relationship between input and output flows is complicated and dependent on many parameters, and it is more appropriate to apply dedicated LCI models. For example, the LCI model PestLCI (Birkved and Hauschild 2006) calculates emissions of pesticides from field applications via different routes (e.g. evaporation, air drift, emissions through drainage pipes and groundwater leaching) based on the application of a specific pesticide to the field, its physical and chemical properties, and a large number of context-specific parameters, such as crop type, time of application, soil pH and slope. Note that the data specificity obtained from LCI models can only be characterised as high if all inputs and parameters are in fact site-specific (and when relevant, time-specific). If this is not the case, the data specificity is lower.

High and very high specificity data (e.g. on elementary flows such as CO_2 emissions and freshwater use) are sometimes available in reports, e.g. 'green accounts' or CSR reports, published by the company operating the process of interest, but often the source of such data is employees working with or operating the process. These may be process engineers monitoring flow data as part of their daily routine, or they may work in the purchasing department and thereby have knowledge about the amounts of input flows (materials and energy) purchased and the identify of suppliers. The latter may be used to contact suppliers for data specific to processes at their sites and the procedure can, in principle, be repeated several times to obtain company internal data further upstream in the foreground system.

Company internal data may be accessed by asking the employees to fill out questionnaires combined with a physical visit to the site, email or telephone contact. This way of obtaining data can be straightforward or require lots of effort depending on the willingness of the employees possessing the data to share them in a relevant format. From our experience, this willingness is generally higher when the commissioner of a study is part of the same company and department as the employee holding the data or if the LCA study has been given attention by the management level in a company. It should be noted that company internal data are sometimes confidential. In some cases, they are not possible to obtain, but in other cases the confidentiality issues may be handled by the LCA practitioner signing a non-disclosure agreement and reporting any confidential data of importance to the study in a special appendix to the report that is only accessible to a selected group of people (typically including members of a peer review panel if the study is peer reviewed).

9.3.2 Medium and Low Specificity Data

For reasons given above it is in practice rarely feasible (nor necessary) to obtain all foreground system data from site measurements, i.e. with high or very high specificity. A large part of the data collection therefore usually takes place online by searching, identifying and accessing publicly available sources, such as other LCA studies, industry association reports and national statistics. It is also possible to identify, via online searching, data for a process that is very similar to the actual process to be modelled, either because the reference flow of the processes is the same (e.g. the incineration of polypropylene) or similar (e.g. the incineration of polypropylene versus polyethylene). The strategy of extrapolation from data for similar processes is especially useful to 'fill out gaps' in a preliminary unit process, but the LCA practitioner must carefully check the representativeness of the process used for extrapolation. For example, if the initial data collection effort has led to a handful of high or very high specificity emission data, but no resource inputs for a process, the remaining flows may be quantified by extrapolation from a similar process. Such similar process can be sourced from scientific papers or other sources, which can document sufficient representativeness (technology, geography, time) and disclose sufficient data to check the agreement with the existing handful of high specificity emission data for the original unit process. A special case of extrapolation is for novel technologies that may not yet operate at industrial scale anywhere at the point in time where the study is to be conducted. Here, an obvious source of extrapolation is laboratory scale processes. It is, however, important to consider how the relationships between the flows of a process changes from laboratory to industrial scale. Often the technology of the process will change, not just in size, at the upscaling from lab scale to commercial scale, and this typically leads to increased efficiency (e.g. less input per reference flow output) and changes in the quality of flows.

The effort required to access data via online searching depends on the expertise of the practitioner (e.g. familiarity with the terminology of the concerned technical domain) and on how well-studied the phenomena behind the data is. For example, there is generally more publically available data on greenhouse gas emissions than on emissions of synthetic chemicals used for very specific industrial purposes and produced in low volumes. The effort also depends on the number of data points that can be accessed from each source. A unit process is often composed of more than 100 flows (the majority often being elementary flows). Some sources, such as LCI databases, contain data for all flows making up a unit process, while other sources, e.g. statistical agencies, may only cover a few elementary flows.

LCI databases are used to source data for the background system and for the parts of the foreground system where more specific data can or will not be obtained. Table 9.5 presents a non-exhaustive list of LCI databases.

Table 9.5 List of process-based LCI databases (not exhaustive)

Name	Description	References
ecoinvent	Swiss database that contains approximately 12,500 processes (version 3) organised under different themes like transport, energy, material production, agriculture, etc. All processes are available as unit- and system-processes and all processes are documented in detail. Updated regularly	ecoinvent; www.ecoinvent.org
ELCD	Database of the JRC of the European Commission, contains more than 300 datasets on energy, material production, disposal and transport	Joint Research Centre of the European Commission; eplca.jrc.ec.europa.eu/ELCD3/index.xhtml
Agri-footprint	A comprehensive LCI database of feed, food and biomass, containing around 3500 products and processes	Blonk Consultants; www.agri-footprint.com
LCA Food	Danish database containing more than 600 data sets on basic food products and related processes from agriculture, aquaculture, fishery, industry, wholesale and supermarket, including waste treatment processes	2.-0 LCA Consultants and Aarhus University; www.lcafood.dk
Swedish National LCA database	Contains more than 500 well-documented LCI data sets in SPINE format for a wide range of industrial processes and household goods and services	Competence Centre for Environmental Assessment of Product and Material Systems of Chalmers University of Technology; cpmdatabase.cpm.chalmers.se
GaBi databases	Separate databases mainly based on primary data collection. Cover sectors from agriculture to electronics and automotive industries, textiles and retail, through to services. Contains more than 10,000 Life Cycle Inventory profiles	GaBi; www.gabi-software.com/international/databases/gabi-databases/
LC-inventories	Over 1000 process data sets, which are corrections, updates or extensions of ecoinvent v2.2 database, created by ESU-Services and other authors	The Swiss Federal Office for the Environment and ESU-services; www.lc-inventories.ch
NEEDS	Database designed for long-term environmental assessment. Contains around 800 processes of future energy supply systems, future material supply, and future transport services	Members of a European research project; www.needs-project.org/needswebdb/index.php
NREL	US-American database with around 300 datasets related to the production of materials, components, or assembly in the U.S.	National Renewable Energy Laboratory; www.nrel.gov/lci
ProBas	Comprises more than 8000 datasets on energy, material production, transport and disposal, different data sources and	German Federal Environmental Agency; www.probas.umweltbundesamt.de/php/index.php

(continued)

Table 9.5 (continued)

Name	Description	References
	data quality. Focuses on processes within Germany	
LCA Commons	More than 18,000 datasets for U.S. agriculture production and agriculturally derived products	USDA; www.lcacommons.gov
Ökobaudat	German database with around 950 environmental product declaration datasets for building materials, building processes and transport processes	Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety; http://www.oekobaudat.de/en.html

While a number of LCI databases are available and some of them contain high-quality data for specific technologies or industries as shown in Table 9.5, the most comprehensive, and probably most widely used, database is ecoinvent and in the following section we there focus on this database and encourage the reader to look for similar information about other databases using the references given in Table 9.5 as relevant. ecoinvent version 3 contains approximately 12,500 unit processes and each process exists in an 'allocation, default' (or APOS: allocation at the point of substitution), an 'allocation, recycled content' (or 'cut-off') and a 'consequential' version. The 'allocation, default' version uses price as allocation key as a rule, except for a few processes, where representative physical parameters are used (such as for processes involving co-production of electricity and heat) where markets are judged distorted by, e.g., regulation, and also corrects for fluctuating prices by applying three-year, historical average prices for some processes (Weidema et al. 2013). The cut-off version is identical to the default allocation version, except for the handling of recyclable materials that are cut-off before being sent to recycling. This means that recyclable materials do not bring any benefits to the primary user of the materials and are considered available 'burden-free' to recycling processes, and that the impacts attributed to secondary recycled materials are only those of the recycling processes and the associated transportation. By contrast, in the default allocation version secondary recycled materials are also allocated a share of the material's previous life cycle impacts (based on economic allocation). The existence of the two allocation approaches for recyclable materials in ecoinvent ('default' and 'cut-off') reflects the fact that there is little consensus on how to perform such allocation in the most reasonable way. The cut-off allocation is the recommended approach in the European Product Environmental Footprint guideline (EC-JRC 2012).

The consequential version of ecoinvent uses the long-term marginal technology, which is identified by considering whether a market is increasing (or stable, or slowly decreasing) or rapidly decreasing, in line with Table 9.1. The ecoinvent centre advocates the use of the consequential version of the database not only for large-scale decisions (studied in Situation B studies, according to ILCD), but also for small-scale decisions, which are by definition too small to cause structural changes outside the foreground system, i.e. too small to lead to new equipment being installed (increase in production capacity) or existing equipment being prematurely taken out of use (decrease in production capacity). Yet the ecoinvent centre argues that the consequential version of the database (which is based on the long-term marginal technology) is "applicable to study the effect of small, short-term decisions, since each individual short-term decision contributes to the accumulated trend in the market volume, which is the basis for decisions on capital investment" (Weidema et al. 2013). In relation to the ILCD-defined decision context situations, the ecoinvent 3 database can, strictly speaking, only be used to model consistently the parts of Situation B studies involving structural changes (using the consequential database) and Situation C2 studies (using the allocation default or cut-off database). However, as noted in Sect. 9.2.2, economic allocation is often the only practical solution to multifunctionality, irrespective of decision context. We therefore advise that one of the two allocation versions of ecoinvent is used for Situation A, B (only non-structural changes), C1 and C2. However, the LCA practitioner should check for any multifunctional processes that have high contributions to early iteration LCA results and, where appropriate and technically feasible, manually change the multifunctionality solution in accordance with the scope definition of the study to test its influence on LCA results.

Whenever data is sourced by online searches or LCI databases it is important to pay attention to the available metadata describing the characteristics and conditions of the process to evaluate how representative the data is for the actual data needed. Metadata usually specifies the exact technology (or mix of technologies, in the case of average or generic data) involved in a process, the location (e.g. country) of the unit process, the time during which the data applies and relevant operating conditions (e.g. climate). The metadata allows distinguishing between medium and low data specificity (see Table 9.4). Relevant metadata for foreground processes should be reported by the LCA practitioner (see Sect. 9.7) and furthermore considered in the later sensitivity analysis and uncertainty management (see Sect. 9.6).

When using a unit process from an LCI database in the foreground system it is preferable to adapt it to make it more representative of the actual process to be modelled to the extent that this is possible (see Sect. 8.7). One improvement of the representativeness that is usually possible is to manually change the electricity grid mix that fuels the process to a mix that matches the geographical and temporal scope of the study. Note that such adaptation is not possible if a unit process is 'aggregated', meaning that the elementary flows of all processes upstream and downstream have been aggregated, so the reference flow is the only output of the aggregated process (or input, in the case of waste treatment processes) apart from the elementary flows.

Aggregated unit processes are often preferred for constructing the background system because the LCA practitioner only needs to include the aggregated processes that link to the foreground processes of an LCI model.

9.3.3 Very Low Specificity Data

If efforts to obtain data have been fruitless, one may rely on expert judgement. People may qualify as experts if they are knowledgeable in the technical domain relevant for the data (e.g. plastic moulding) or if they have conducted similar LCA studies themselves in the past. If no expert is available, a last resort is to use a 'reasonable worst case' for the calculation of the first iteration of LCA results. A reasonable worst case value may be derived from knowledge of similar or related processes or from correlation or calculation from other flows of the process or other processes. The results will then show if the data is potentially important or negligible (judging against the cut-off criteria identified in the scope definition). In the first case, the practitioner may try again to obtain data of better quality or address the issue in the interpretation of results. In the latter case, the reasonable worst case data may either be kept in the model or removed. Whatever option is chosen it should be reported (see Sect. 9.7) for the sake of other LCA practitioners wanting to use (parts of) the inventory model in future LCA studies.

9.4 Constructing and Quality Checking Unit Processes

The data that is collected should represent full operation cycle of the process, including preparatory activities like heating, calibration (with potential loss of materials and products as scrap), operation, idling, cleaning and maintenance. It should also take into account typical scrap rates during operation. This means that the data collection should be based on a longer period of operation, ideally covering several production cycles, perhaps one year's production. Sometimes also the impacts from the manufacturing and end-of-life stage of the production equipment are important and then they should also be included in the data collection. When the data has been collected, it is time to construct unit processes. As mentioned, the type of data collected can vary (see Table 9.3) and it is important to ensure that all the data has the right format for a unit process. To reiterate, all data must be in the form of flows. Elementary flows must be in a unit that matches that of the characterisation factors to be applied ('kg' in many cases), and all flows should be scaled to 1 unit of the reference flow of a unit process (see Figs. 9.6 and 9.7). Note that unit processes obtained from LCI databases already have the right format and are therefore ready to incorporate in an LCI model (see Sect. 9.5).

9.4.1 Quality Check of a Unit Process

When constructing unit processes there is a risk that they are incomplete and that there are errors in the flow quantities. Incompleteness may be caused by the fact that some flows are not monitored or reported. Errors in flow quantities may be caused by errors in reported measurements (e.g. a technician writing ‘g’ instead of ‘mg’) or errors in the calculation of flows and conversions of units (e.g. if one had forgotten to convert the concentration unit in the example of Fig. 9.7). To avoid (critical) incompleteness and quantitative errors, constructed unit processes should be checked before they are used in an LCI model. Such a quality check can be supported by calculation and interpretation of first iteration LCIA results, e.g. through the identification of the most contributing process and substances.

Completeness of flows

There are three complementary approaches for validating the completeness of flows.

1. Knowledge of similar processes can help identifying potentially missing flows. For example, the LCA practitioner may suspect one or more missing flows, if a unit process for a specific paper production process contains no chlorine containing compounds in the wastewater to treatment and the practitioner knowns from previous experience that chlorine compounds are typically present in the effluent of paper production processes.
2. Knowledge of the nature of a physical transformation in a process can hint what emissions or waste flows to treatment may be missing. For example, NO_x gases are known to be formed whenever a combustion process occurs in the presence of nitrogen, the major constituent of atmospheric air. Filters can capture large fractions of generated NO_x before it becomes an emission, but usually not every single molecule.
3. A qualitative comparison of input and output flows can show if there is disagreement between the elements entering a process and the elements leaving a process. For example, a process cannot emit large quantities of CO_2, without inputs of carbon sources in the form of fossil fuels (e.g. coal, natural gas or oil). While using this validation technique it should be kept in mind that some flows entering and leaving a process are elementarily heterogeneous. For example, mercury is a common emission from the combustion of coal due to the mercury content (typically in the order of 0.00001%) of the coal entering the process as a heterogeneous material flow. In this case, the mercury input is ‘hidden’ in the coal input and it would therefore be wrong to assume that a homogenous input of mercury is missing on account of the emission of mercury.

Flow quantities

A unit process should obviously not only contain the right flows, but also the right quantities of these flows. A number of validation approaches exist for checking flow quantities.

A mass balance is a universal approach because the sum of flows entering a process should amount to the same number as the sum of flows leaving a process since no accumulation occurs inside the process. A mass balance is therefore an efficient way of spotting errors, for example if the mass of outputs is on the order of

1000 times the mass of inputs. Note, however, that flow quantities may be correct, even if the law of conservation of mass seems to be violated. This is because most of the constituents of atmospheric air, e.g. oxygen and nitrogen, are generally not counted as resource inputs in unit processes, in which case the mass of outputs appear larger than the mass of inputs (e.g. due to combustion products such as CO_2, H_2O and NO_x). A mass balance can also be applied at the level of individual elements, but one should be aware of 'hidden' elements in heterogeneous flows, as described above. Energy balances can in principle also be used as a validation approach, but this would require calculations of the chemical energy stored in inputs and outputs and quantification of heat lost to the environment, which is often not reported as an emission in a unit process.

Following validation based on mass balance a complementary validation based on stoichiometry can be carried out if the process to be validated involves one or more chemical reactions. This serves to check if the ratio between inputs and outputs involved in a chemical reaction is correct. For example, stoichiometry gives us the correct ratio between inputs and outputs in the electrolysis of water in the presence of sodium chloride: $2NaCl + 2H_2O \rightarrow 2NaOH + H_2 + Cl_2$. The mass (g) of each molecule can then be calculated by multiplying its stoichiometric coefficient (mole) and its molar mass (g/mole).

Other validation approaches rely on comparisons to external information. This could be information for similar processes that are expected to contain flows of similar magnitudes as the process to be validated. The external information could also be legal limits. For example, if an emission of nitrogen dioxide corresponds to 100 times a regulatory emission limit, it is a strong indication that there is an error in the emission quantity (note however that many regulatory limits are given as concentrations rather than mass flows, in which case a conversion is needed).

Yet another validation approach relies on the first iteration of LCIA results. These are useful for identifying erroneously high flow quantities. For example, if the contribution from a single elementary flow of a single unit process contributes with 99.9% of the impact for an impact category, this is a strong indication that the flow quantity is too high (e.g. due to a factor 1000 unit conversion mistake in a calculation or data entry in the LCA software). This validation approach can also be used to check for mistakes in the ID of an elementary flow, such as mistakenly using the name 'dioxin' for an emission of 'carbon dioxide' (dioxin is a group of extremely toxic chemicals).

9.4.2 Using Flow Names Compatible with LCA Software

To prepare a unit processes for use in an LCI model it is important that the LCA software used 'understands' the identity of the flows of the unit process. If this is not the case, a flow cannot be linked correctly to other processes or characterisation factors (in the case of elementary flows). There have been attempts at harmonising flow names across LCI databases and LCA software, but the LCA practitioner should always check the flow nomenclature of the software used (e.g. SimaPro, GaBi or OpenLCA) and follow this when naming the flows of constructed unit processes. Unit processes of LCI databases (see Table 9.5) are commonly integrated into LCA software, which ensures that their flow names are correct.

LCA practitioners may face a situation where an LCA software has no name for a given elementary flow or the CAS-number (Chemical Abstract System number—a unique identifier for a chemical) of an emitted chemical does not exist in the list of flow names in a software. In this case, the LCA practitioner should check if there is a characterisation factor (CF) for the chemical in the LCIA method to be applied in the ensuing LCIA step. If this is the case, the LCA practitioner should create a new flow in the LCA software with a name identical to the name of the CF, so the software can create the link. If there is no CF, the LCA practitioner can either calculate the CF on his/her own when guidelines to do so exist (e.g. for the USEtox model; see Chap. 40) or discuss the potential of that substance to contribute to the total environmental impact and to the resulting interpretation of the results. In the case of missing flows that are not elementary flows, these should also be created in the LCA software and used to link processes together. For example, in the case of a waste to treatment flow that is specific to the studied system (part of the foreground system), and therefore not existing in the LCA software, this flow should be created in the software and used to link the process having it as an output to the most appropriate waste treatment process that is available.

9.5 Constructing the LCI Model and Calculating LCI Results

When all unit processes have been constructed or collected from LCI databases the LCA practitioner can construct the LCI model. Each unit process can be seen as a ‘building block’ in the LCI model, the ‘size’ of which is ultimately decided by the study’s reference flow derived from the functional unit in the scope definition (see Chap. 8). This is because the reference flow decides the quantity required of each unit process-specific reference flow. In other words, each unit process must be scaled to fit the LCI model. Figure 9.8 shows an example of how this is done manually for a simplified system composed of just three unit processes each having just 4 flows.

In Fig. 9.8, Process 1 is first scaled to match the reference flow of the study (100 kg of Product *X*). After the scaling of Process 1, 200 kg of Product *Y* is required, which Process 2 is scaled according to. This means that 240 kg of Product *Z* is required, which Process 3 is scaled according to, etc. In practice, LCA software can carry out the scaling automatically for the practitioner, when told what the reference flow of a study is.

In practice, inventory modelling is normally performed using a dedicated software which supports both the building of the product system model, connecting the

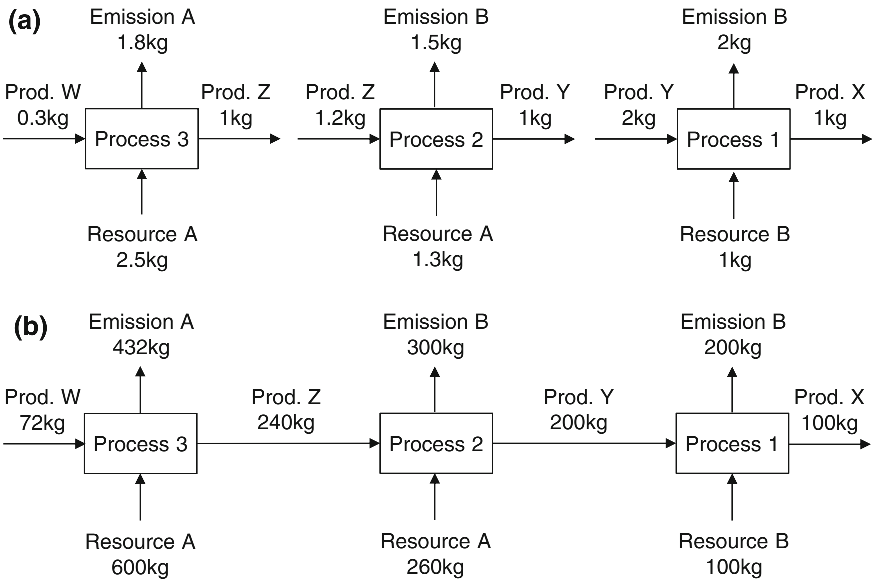


Fig. 9.8 Three simplified unit processes unconnected (**a**) and connected (**b**) based on a study reference flow of 100 kg of product *X* (the reference flow of process 1)

Table 9.6 Software for performing LCA (non-exhaustive list)

Name	Information
SimaPro	Pré Consultants; www.pre-sustainability.com/simapro
GaBi	Thinkstep; www.gabi-software.com/international/index/
OpenLCA	GreenDelta (open access); www.openlca.org/
Umberto	Ifu Hamburg; www.ifu.com/en/umberto/

relevant unit processes; the linking to available unit process databases and storing of own processes, and the linking of elementary flows in the inventory results to the relevant characterisation factors for the life cycle impact assessment. Table 9.6 shows some of the widely used software for LCA

9.5.1 Database and Software Specific Aspects

As mentioned in Sect. 9.3.2 processes from LCI databases exist in disaggregated and aggregated versions, the difference being that the latter scales all processes upstream and downstream according to the reference flow of the process and aggregates their elementary flows, so that the only output of the aggregated process (or input, in the case of waste treatment processes) that is not an elementary flow is its reference flow. In practice, some LCI databases only provide aggregated processes, which means that it is not possible to modify them to increase their representativeness for the study. When aggregating processes, the LCI database providers have made choices on how to handle multifunctional processes and how to cut-off the life cycle of the process' reference flow because including all processes is not practically achievable in process-based LCI modelling (see Sect. 9.1). These choices also relate to solving the issue of closed loops between processes, which occurs if two processes need each other's outputs as inputs. This issue is commonly solved by matrix inversion (Heijungs and Suh 2002).

The way system expansion is performed in the construction of the inventory model depends on the LCA software used, but it is usually simple to implement for the LCA practitioner. For example, in GaBi it is performed by connecting the avoided process as input but with a scaling factor of −1 so that it is computed negatively as a crediting. In SimaPro, system expansion is performed by making a direct link to the avoided process in the flow category 'Avoided products', and the software automatically accounts for it negatively when processing the assessment. In OpenLCA, which is a free LCA software, system expansion is modelled as an avoided output of a unit process, in practice marking an output flow as 'avoided product' by checking a mark in the process.

9.5.2 Calculation of LCI Results

The LCI results are the compilation of elementary flows over all the processes that are part of the LCI model (scaled to the reference flow of the functional unit). For the simplified product system in Fig. 9.8 the results would simply be the sum of each of the resources and emissions across all the processes, see Fig. 9.9 describing final LCI results.

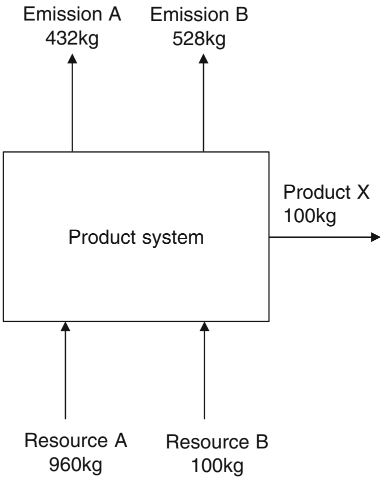


Fig. 9.9 LCI results for the product system in Fig. 9.8. The aggregated elementary flows of product *W* (72 kg), that are not shown in Fig. 9.8, are 100 kg of resource A and 28 kg of emission B

In practice, the number of flows and processes is normally huge, but no manual work is typically required from the LCA practitioner as the LCA software can calculate LCI results for a product system with one click of a mouse button. Such LCI results are the basis for the subsequent life cycle impact assessment phase (unless the goal of a study is to simply calculate the LCI results).

9.6 Data Needs for Uncertainty and Sensitivity Analysis

Uncertainty and sensitivity analysis is important for the interpretation of LCIA results because they can inform the LCA practitioner on how robust the conclusions of the study are and where future studies should focus to make results even more robust. Chapter 11 is dedicated to these matters and details the theoretical background and the practical use of uncertainty and sensitivity analyses. The following describes the data that needs to be collected during the inventory analysis as inputs for uncertainty and sensitivity analyses.

Uncertainty analysis allows for the quantification of uncertainties of the final result, as a consequence of the uncertainty of each parameter in the LCI model. To enable an uncertainty analysis, the practitioner must, for quantitative parameters in the foreground system, collect information on their statistical distribution (e.g. normal, log-normal or uniform) and corresponding statistical parameter values (e.g. mean and standard deviation for normally distributed parameters).

Sensitivity analysis allows for systematic identification of the parameters that have the highest influence on the LCIA results. The influence of parameters on results is calculated by changing them, one by one, and observing the changes in results. These changes in parameters should reflect uncertainties about the actual product system modelled. For quantitative parameters in the foreground system, the practitioner should aim to collect minimum and maximum values, or a low and a high percentile (e.g. 2.5th and 97.5th) when a parameter's statistical distribution is known (see above), in addition to the default value that is used in the LCI model. For example, a specific farmer may on average apply 2 kg of a specific pesticide to produce 1 tonne of potatoes, but this number may vary from 0.5 to 3 kg, depending on weather conditions. For discrete parameters or assumptions in the foreground system the practitioner should develop a number of sensitivity scenarios. For example, a part of the product system may be located in a different country than assumed in the LCI model and a sensitivity scenario would thus involve differences in energy mix, waste treatment technologies, etc. Note that the data requirements for sensitivity and uncertainty analysis overlap and data collection can therefore be performed in parallel by the practitioner.

It often takes more time to collect sensitivity and uncertainty data for some parameters in the foreground system than for others and it may not be necessary to collect data for all processes, depending on the outcome of the first iteration of the analysis. For example, if a process is found to contribute to less than 0.1% of total impacts, then its sensitivity and uncertainty data should generally not be a high priority as illustrated by Fig. 12.3.

For the background system, many LCI databases include uncertainty information on processes, which can feed into uncertainty and sensitivity analysis in LCA software. The practitioner therefore needs not to bother about such data in the inventory analysis.

9.7 Reporting

The reporting of the inventory analysis should contain six elements:

1. Documentation of LCI model at system level.
2. Documentation of each unit process.
3. Documentation of metadata.
4. Documentation of LCI results.
5. Assumptions for each life cycle stage.
6. Documentation of data collected for uncertainty and sensitivity analysis.

Elements 1, 2 and 3 should allow the reader to recreate the LCI results, which are documented in Element 4 (i.e. exigence of reproducibility of the study). Element 5 should allow the reader to judge the reasonability of all assumptions performed (i.e. exigence of transparency) and Element 6 should allow the reader to recreate the uncertainty and sensitivity analysis (exigence of reproducibility and consistency). Below we elaborate on each element and we further refer to the illustrative case on window frames in Chap. 39 for an example of how the inventory analysis may be reported.

9.7.1 Documentation of LCI Model at System Level

We propose to use a flowchart that contains all the linked processes in the foreground system for each studied product system and shows their links to processes in the background system. Each process should be named and, depending on the size of the foreground system, flow names and quantities may also be given (this information is, however, not essential, as it will also be given in second reporting element). Figure 9.10 illustrates how to document a flow chart for a simple, hypothetical LCI model (flow names and quantities not shown). Flow chart should be reported in the main part of an LCA report.

Note that only the unit processes of the background system that are linked to (‘neighbouring’) the foreground system needs to be included in the flow chart. These are processes UP1 to UP8 in Fig. 9.10. From this information, the reader

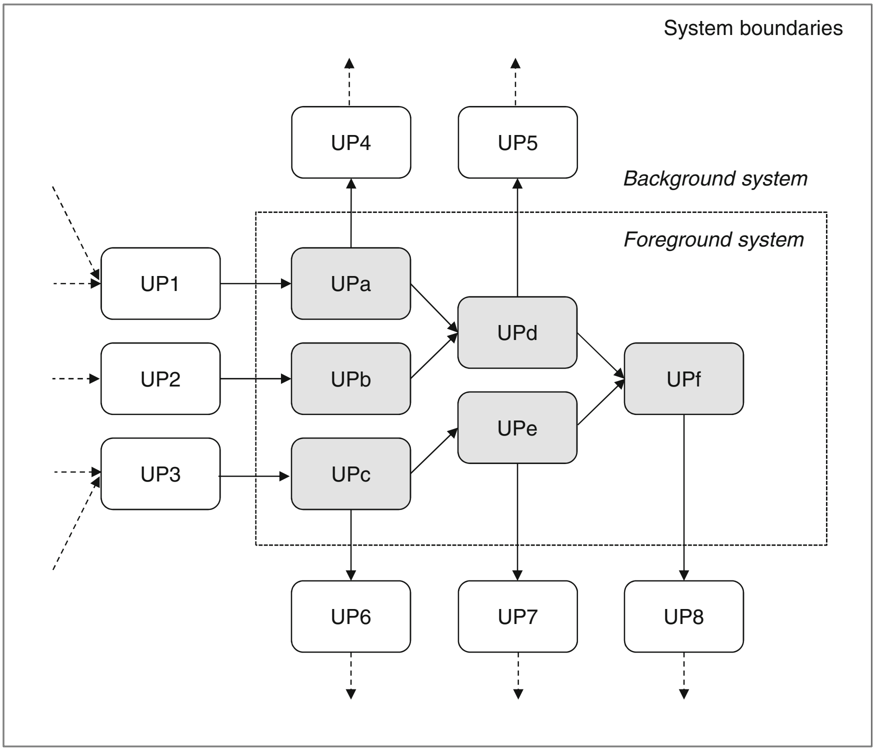


Fig. 9.10 Documentation of LCI model in flow chart. *Arrows* between unit processes (UPs) indicate material, energy, product or waste flows. Unit processes belonging to the foreground and background system are identified with a *letter* or with a *number* respectively. Only the background unit processes neighbouring the foreground system should be included and *dotted arrows* to and from these processes indicate the existence of additional background processes.

may reconstruct the remaining background system on his/her own by using aggregated versions of the reported 'neighbouring' background processes from the relevant LCI database(s).

9.7.2 Documentation of Each Unit Process

We recommend the creation of a table for each unit process in the foreground system that contains its name (identical to the one used in the flow chart of the first reporting element) and the names and quantities of all flows (materials, energy, resources, products, waste to treatment and emissions—same units as used in LCA software), see scheme in Table 9.7. We also advocate providing the source of a process or flow (e.g. name of the database where process is from), a reference to the

Table 9.7 Scheme for documenting foreground processes

Outputs	Quantity	Unit	Source/note
Reference flow (main product or function)			
Reference flow	1	kg	E.g.: input and output flows are not scaled to the functional unit of the product system
Other outputs (avoided product or function; waste to treatment)			
Avoided product 1	–	kg	E.g. please see Table A1 for the corresponding unit process
Waste 1	–	kg	E.g. ecoinvent ver. 3.0
Waste 2	–	m^3	E.g. ecoinvent ver. 3.0
Waste *n*	–	m^3	E.g. ecoinvent ver. 3.0
Emissions (to air; water; soil)			
Emission 1	–	kg	E.g. please see "Appendix" for details on calculation of emissions
Emission 2	–	kg	E.g. please see "Appendix" for details on calculation of emissions
Emission *n*	–	m^3	E.g. please see "Appendix" for details on calculation of emissions
Inputs	Quantity	Unit	Source/note
Materials			
Material 1	–	kg	E.g. please see Table A2 for the corresponding unit process
Material 2	–	kg	E.g. please see Table A3 for the corresponding unit process
Material *n*	–	m^3	E.g. ecoinvent ver. 3.0
Energy			
Energy 1	–	MJ	E.g. ecoinvent ver. 3.0; see Table 1 in the main report for the source of values
Energy 2	–	MJ	E.g. ecoinvent ver. 3.0; see Table 1 in the main report for the source of values
Energy n	–	MJ	E.g. please see Table A4 for the corresponding unit process
Resources			
Resource 1	–	kg	E.g. ecoinvent ver. 3.0
Resource 2	–	kg	E.g. ecoinvent ver. 3.0
Resource *n*	–	m^3	E.g. ecoinvent ver. 3.0
			E.g. ecoinvent ver. 3.0

Units are illustrative. *Note* that for waste treatment processes the reference flow is usually a material input. *Note* that the column 'source/note' is based on fictive examples and references included therein are not a part of this textbook chapter

section of a report where details of a calculations (e.g. emissions) are provided; and finally, reference to other unit process tables that are input or output to the process of interest. Because the number of processes to be documented is often large, tables like Table 9.7 are usually best reported in an appendix to the LCA report.

The flow quantities of process tables should either be scaled to 1 unit of the reference flow of the process (as shown in Table 9.7) or scaled to the quantity of process reference flow required to meet the reference flow of the study (derived from the functional unit). For neighbouring background processes (UP1 to UP8 in Fig. 9.10), the name of the process and the name and version of the database it was sourced from is sufficient, because the reader may use this information to recreate the remainder of the background system.

Note that inventory data in the foreground system are sometimes confidential, for example when a manufacturer wants to prevent the details of the production processes to be disclosed to the public or competitors. In terms of documenting LCI results, confidentiality issues can be handled by placing the process tables containing confidential data in an appendix that is only made available to groups of people that are cleared by the supplier of the data (e.g. employees of the organisation commissioning a study and an external critical reviewer).

9.7.3 Documentation of Metadata

We recommend reporting metadata according to specificity, type, source and access using the structure of Table 9.2 (introduced for data planning and collection). For easy overview, the rows of the table should be grouped into life cycle stages. The data specificity classification (from very low to very high) for each data point should be transparent, i.e. by writing in the relevant cell why a data point was classified to a given specificity, rather than simply making a cross. The documentation of these metadata should be consistent with the documentation of unit processes described in Table 9.7, and cross-references between the two should be made (e.g. notes and data sources reported in tables documenting unit processes may readily refer to the table with metadata) We advocate reporting metadata in the main part of the LCA report.

9.7.4 Documentation of LCI Results

The LCI results should simply be documented as a list of quantified elementary flows, divided into resources and emissions, i.e. as in Table 9.7. This typically consists of an extensive table, which can be documented as an appendix for readability of the LCA report.

9.7.5 Assumptions for Each Life Cycle Stage

Due to lack of information and budget constraints, it is common to make several assumptions when constructing an LCI model. For example, data originally planned to be collected in medium or high specificity may end up being collected in low specificity. Thereby assumptions need to be made on what low-quality data can best represent the actual data. For example, should a wastewater treatment process in Vietnam, for which data could not be obtained, be approximated by a process in Thailand, possibly correcting for the Vietnamese electricity mix, or should it rather be approximated by an average process for the entire South East Asian region? All assumptions made during the construction of the LCI model should be transparently documented. We recommend that major assumptions are indicated, when describing the data collection and modelling of each individual life cycle stage, to facilitate cross-comparison with the documentation of metadata. Major assumptions may also be included directly in the table containing metadata. References to the sensitivity analysis should be given for assumptions whose influence on LCIA results are tested by the creation and analysis of sensitivity scenarios (see next subsection). We also recommend that a list of all assumptions, minor and major, be placed in an 'Appendix'.

9.7.6 Documentation of Data Collected for Uncertainty and Sensitivity Analysis

For sensitivity analyses, the LCA report must state which parameters are analysed and whether this is done by calculating normalised sensitivity coefficients (for parameters of a continuous nature) or by the construction of sensitivity scenarios (for parameters of a discrete nature). In the former case, the perturbed values for each parameter must be documented and the basis of these explained (e.g. reported min/max-values, 2.5/97.5 percentiles, or an arbitrary value, such as ±10%). In the latter case, the sensitivity scenarios should be documented and references to the assumptions they are based on made (see previous subsection).

For uncertainty analyses, the best practice is to use statistical distributions of parameter values as input to Monte Carlo analysis (see Sect. 9.6), in which case the distributions (e.g. uniform, normal or log-normal) and statistical parameters (e.g. standard deviation) must be documented for each parameter value covered in the uncertainty analysis. If, due to lack of such data, the Pedigree approach is taken, the underlying uncertainty factors and calculated geometric standard deviation for process must be documented. An example was given earlier in Table 9.6.

Appendix: Example of Consequential LCA on Biodiesel Made from Poultry Fat

To help you get an overview of the 4-step procedure for performing a consequential LCI (presented in Sect. 9.2.3), an example is here presented, which shows some parts of a consequential LCI looking at the decision to supply additionally 200 tonnes of biodiesel based on poultry fat. It should be noted that this is a constructed example and that the factual claims made may not be completely accurate.

To start the procedure, we go to Step 1. Here we are asked to consider whether the assessed decision leads to changes in demand or supply. Clearly, this decision leads to changes in supply. This implies that we move directly to Step 3.

Step 3 is based on the assumption that demand is constant, and given that we increase supply of poultry fat biodiesel we therefore have to consider what other products it substitutes. According to the procedure given in Step 3, we need to identify a user and a satisfying substitute for the user which fulfils the same functions terms of functionality, technical quality, costs, etc.

Biodiesel is only used by drivers of diesel vehicles and can be blended with petrochemical diesel or used as a full substitute for petrochemical diesel in ordinary diesel engines. As it is often sold under favourable tax conditions, it seems reasonable to assume that it will substitute ordinary diesel. However, another scenario which may also in some cases be realistic to consider is that it will substitute other types of biodiesel (e.g. based on other substrates). Ordinary diesel and other types of biodiesel can both be produced without constraints (the answer to the second question of the decision tree in Fig. 9.5 is 'no') and can therefore both be considered reasonable alternatives. In this example, however, we will only consider the former.

Having found petrochemical diesel as a substitute, we go to Step 4 to identify which technology will produce the diesel, which is substituted. Here, we need to consider the trend in the market, the scope of the decision, and whether the decision leads to an increase or decrease in demand. Having addressed these issues, we find that the substituted diesel is produced by the least cost-efficient technology supplying the market at the time of our decision, which we find to be crude oil produced from tar sand.

Biodiesel does not contain the same amount of energy per weight unit as ordinary diesel, implying that we will need more biodiesel than diesel to drive a certain distance. The ratio is around 37:42, implying that for each kg of poultry fat biodiesel we produce and use extra, we will reduce the production and use of diesel made from tar sand by 37/42 kg.

The production of biodiesel inevitably leads to the co-production of glycerol. When we decide to increase the production of biodiesel by 200 tonnes, we will also increase the production of glycerol by approximately 20 tonne. As this is a result of our decision to produce more biodiesel, it needs to be included in the assessment. We therefore start again in Step 1 by asking the question: "What happens if we increase the supply of glycerol by 20 tonnes?" Being a supply oriented question, we go directly to Step 3, where we are asked to identify products for which glycerol can serve as a substitute, based on relevant functionality, technical quality, costs, etc. Through analysing the biodiesel market, for example through biodiesel journals and experts in the field, we find that glycerol from biodiesel can be used by producers of chemicals, especially for the production of propylene glycol. Hereby glycerol can, after distillation and processing, substitute other feedstock in the production of propylene glycol. Having identified a substitute, we go to Step 4, to identify the propylene glycol production technology affected by the change in feedstock to glycerol. This procedure (not detailed here) allows us to include the avoided production of propylene glycol in our LCI. When doing so, it is important to identify the processes needed to convert the crude glycerol to propylene glycol and remember to take into consideration the conversion rate.

Having considered both the substitution of diesel with biodiesel and conventional propylene glycol with propylene glycol made from glycerol, we have now considered all the downstream parts of the life cycle. However, our decision to supply more poultry fat biodiesel will also create changes in the upstream part of the life cycle: If we want to supply more poultry fat biodiesel, we need more of the constituents included for producing the biodiesel. The demand for these constituents thereby increases. In the concrete case, biodiesel is made from poultry fat and methanol, which are brought to react using a strong base, often sodium hydroxide. For the sake of simplicity, we will here only consider the increased demand for poultry fat and methanol.

Thus, we return to Step 1 and ask: "What happens if I increase the demand for poultry fat?" As this is clearly a question that relates to demand, we go to Step 2.

The first part of the decision tree in Step 2 (Fig. 9.4) asks us to consider whether the production of the product is constrained. In this case, this is actually the case, since poultry fat is a low value by-product from the production of other poultry products, mainly meat. The production of poultry fat therefore follows the demand for poultry meat, and additional demand for poultry fat will not result in an additional supply of poultry fat. As the assessed decision will lead to an increase in the demand for poultry fat, and as market analysis shows us that poultry fat is already used to the extent the constraint of being a co-product allows (in other words, no poultry fat is wasted), we go to Step 3, to find out which product can substitute our use of poultry fat. Poultry fat is mainly used in the feed industry and through contacts to feed producers we find that they are able to use palm and soybean oil in a certain relationship instead of poultry fat. This implies that if we decide to produce more biodiesel from poultry fat and thereby demand more poultry fat, we will not increase the supply of poultry fat but rather increase the demand for palm and soybean oil. To identify the consequences of the increased demand for these oils, we go through the relevant Steps 2–3 for each of these, but to keep this example relatively simple, we will not go further into documenting these steps.

Assuming that we have now fully outlined the processes that change as a result of our increase in demand for palm and soybean oil, we turn to the other main constituent of biodiesel, namely methanol. As noted above, we also increase the demand for methanol. We therefore again start in Step 1 by asking the question: "What happens when I increase the demand for methanol?" As this is a demand oriented question, we go to Step 2. Here we are first asked whether methanol can be produced without constraints. As this is the case, we go to Step 4. Here we are asked to consider the overall trend in the market, the scope of the decision in comparison to the overall market for methanol, and whether the decision leads to an increase or decrease in demand. Through market studies we find that the trend in the market, which can be considered global, is an increasing production. Secondly, the size of the decision, which in this case is to produce a few hundred extra tonnes of poultry fat biodiesel will amount to very little compared to the overall market volume for methanol. We should therefore identify the *short-term* marginal producer.

Given that our decision leads to an increase in demand, we are told by Table 9.1, that the methanol will be produced by the least competitive producer on the market. As there are more or less only producers making methanol from synthetic gas, we assume that the methanol will be produced using this technology.

Other inputs and outputs to and from the biodiesel process are handled in a similar way, but to keep the example relatively short, these will not be discussed here.

As the example shows, creating a consequential LCI is in many cases a rather laborious task as detailed knowledge is needed about the markets affected by the decision, as for example establishing knowledge about potential substitutes for poultry fat in the feed industry in the example above. Much of the time spent making the LCA will therefore often be used in preparing the consequential LCI.

References

This chapter is to a large extent based on the ILCD handbook and the ISO standard 14040 and 14044. Due to the scope of this chapter, some details have been omitted, and some procedures have been rephrased to to make the text more relevant to students. For more details, the reader may refer to these texts:

EC-JRC: European Commission—Joint Research Centre—Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook—General guide for Life Cycle Assessment—Detailed guidance, 1st edn. March 2010. EUR 24708 EN. Luxembourg, Publications Office of the European Union (2010)

ISO: Environmental Management—Life Cycle Assessment—Principles and Framework (ISO 14040). ISO, the International Organization for Standardization, Geneva (2006a)

ISO: Environmental Management—Life Cycle Assessment—Requirements and Guidelines (ISO 14044). ISO, the International Organization for Standardization, Geneva (2006b)

Additional References Used in the Text

Birkved, M., Hauschild, M.Z.: PestLCI—a model for estimating field emissions of pesticides in agricultural LCA. Ecol. Model. **198**, 433–451 (2006). doi:10.1016/j.ecolmodel.2006.05.035

Ciroth, A.: Refining the pedigree matrix approach in ecoinvent: towards empirical uncertainty factors. Presentation at the LCA Discussion Forum Zürich, 13, September 2013 (2013)

EC-JRC: Product Environmental Footprint (PEF) Guide. Deliverable 2 and 4A of the Administrative Arrangement between DG Environment and the Joint Research Centre No N 070307/2009/552517, including Amendment No 1 from December 2010. Ispra, Italy (2012)

Goedkoop M, Oele M, Leijting J, et al.: Introduction to LCA with SimaPro. Report version 5.2, January 2016 (c) 2002–2016 Pré. (2016). www.pre-sustainability.com

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.A., de Bruijn, H., van Duin, R., Huijbregts, M.A.J.: Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Kluwer Academic Publishers, Dordrecht (2002). ISBN 1-4020-0228-9

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

Weidema, B.P.: Market Information in Life Cycle Assessment. Environment Project No. 863, vol. 863, p. 147 (2003)

Weidema, B.P., Bauer, C., Hischier, R., et al.: The ecoinvent database: overview and methodology. Data Quality Guideline for the Ecoinvent Database Version 3 (2013). www.ecoinvent.org

Wenzel, H., Hauschild, M.Z., Alting, L.: Environmental assessment of products. In: Methodology, Tools and Case Studies in Product Development, vol. 1, 544 pp. Chapman & Hall, Kluwer Academic Publishers, Hingham, MA (ISBN:0 412 80800 5) (1997)

World Coal Association: Coal and steel statistics 2012 (2012)

World Steel: World steel in figures 2015 (2015)

Author Biographies

Anders Bjørn Part of the LCA community since the early 2010s. Main focus is interpretations of sustainability and integration of sustainability targets in LCA to enable absolute sustainability assessments.

Andreas Moltesen Has been working with LCA since 2006 with a particular focus on social life cycle assessment. He has later worked on life cycle assessments of biofuels and is currently particularly involved with life cycle assessments of transport systems.

Alexis Laurent Working with LCA since 2010 with a strong LCIA focus, particularly on normalisation aspects. Main LCA interests include development of LCIA methods, LCA applications and footprinting of large-scale systems for policy-making (e.g. nations, sectors), and LCA applied to various technology domains, including energy systems.

Mikołaj Owsianiak Involved in development and application of life cycle impact assessment methods in sustainability assessment of technologies. Has worked on issues associated with: soils (remediation), metals (toxic impact assessment), biodiesel (fate in the environment), and carbonaceous materials (biochar and hydrochar).

Andrea Corona Materials engineer with a focus on sustainability assessment of biobased products and composite materials. Working with LCA from 2012. Main interests include life cycle engineering, product development and eco-design

Morten Birkved With a background in environmental chemistry and LCA, Morten's primary research activities are focused on the development of quantification methods for ecosphere-technosphere exchanges, general LCI, scope modelling, assessment of buildings and built environments, system modelling and fused assessment forms.

Michael Z. Hauschild Involved in development of LCIA methodology since the early 1990s. Has led several SETAC and UNEP/SETAC working groups and participated in the development of the ISO standards and the ILCD methodological guidelines. Main LCA interests are chemical impacts, spatial differentiation and science-based boundaries in LCIA.