Chapter 8
Scope Definition

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Abstract The scope definition is the second phase of an LCA. It determines what product systems are to be assessed and how this assessment should take place. This chapter teaches how to perform a scope definition. First, important terminology and key concepts of LCA are introduced. Then, the nine items making up a scope definition are elaborately explained: (1) Deliverables. (2) Object of assessment, (3) LCI modelling framework and handling of multifunctional processes, (4) System boundaries and completeness requirements, (5) Representativeness of LCI data, (6) Preparing the basis for the impact assessment, (7) Special requirements for system comparisons, (8) Critical review needs and (9) Planning reporting of results. The instructions relate both to the performance and reporting of a scope definition and are largely based on ILCD.

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

- Define the scope of any LCA study.
- Explain each of the nine scope items and their relevance for the subsequent LCA phases.
- Define a functional unit for any kind of LCA study.
- Explain the fundamental characteristics of an attributional and a consequential modellingapproach and how the decision context determines the choice between them.
- Explain how the iterative approach to LCA helps getting the system boundaries and completeness right.

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8.1 Introduction

The scope definition determines what product systems are to be assessed and how this assessment should take place. Together with the goal definition (Chap. 7) the scope definition serves as a firm guide for how the ensuing LCA phases should be performed (Inventory analysis, Impact assessment and Interpretation, including uncertainty and sensitivity analysis) and for how the LCA should be reported. An overarching aim of the scope definition is to ensure and document the consistency of methods, assumptions and data and strengthen the reproducibility of the study.

A scope definition consists of the following nine scope items:

1. Deliverables
2. Object of the assessment
3. LCI modelling framework and handling of multifunctional processes
4. System boundaries and completeness requirements
5. Representativeness of LCI data
6. Preparation of the basis for the impact assessment
7. Special requirements for system comparisons
8. Needs for critical review
9. Planning reporting of results.

Each item must be considered when performing an LCA. Items 2–6 are central for *doing* an LCA because these have a pervasive influence on decisions made in later LCA phases. Aspects 1, 7, 8 and 9 mainly relate to *reporting and communicating* an LCA study. For these items, we further refer to Chaps. 13, 37–39, which provide specific guidance on the reviewing and reporting of LCAs. Note that the aspect of data quality requirements, which ILCD proposes as a separate scope item, is here considered under scope items 4 and 5.

8.2 Terminology and Key Concepts

Before explaining the nine scope items, we present the terminology and key concepts that are used in this chapter.

8.2.1 Unit Process and Flows

A unit process is the smallest element considered in a life cycle inventory model (see below) for which input and output data are quantified. Unit processes can therefore be considered the building blocks of a life cycle inventory model that are "glued together" by input and output data, which can be organised into six categories of physical flows:

Input flows:

1. Materials
2. Energy
3. Resources

Output flows:

4. Products
5. Waste to treatment
6. Emissions.

Figure 8.1 shows a unit process of steel sheet rolling with an example of flows for each of the six categories.

In practice, a unit process can represent a single process, e.g. the rolling of steel, but it can also represent an entire facility that contains many different processes, e.g. a slaughterhouse, if this offers the sufficient level of detail for the inventory modelling. The latter type of unit process may be physically subdivided into two or more new unit processes in a life cycle inventory model, see Sect. 8.5.4. Generally, unit processes do not gain or lose mass over time and the sum of all input flows-should therefore be equal to the sum of all output flows at the level of elements (e.g. copper) and in aggregation.

Output flows belonging to the *product* or *waste to treatment* categories from one unit process can act as input flows belonging to the categories *materials* and *energy* for other unit processes and this is how unit processes are linked in a life cycle inventory model. By comparison, resources and emission flows are not exchanged between unit processes. They are referred to as *elementary flows*, and defined by ILCD (using a slight modification of the ISO definition) as "single substance or energy entering the system being studied that has been drawn from the ecosphere without previous human transformation, or single substance or energy leaving the system being studied that is released into the ecosphere without subsequent human transformation". The ecosphere can be understood as "the environment" and is elaborated below. Note that a single substance should be seen as an ideal and that some elementary flows in existing LCA practice are heterogeneous materials (such

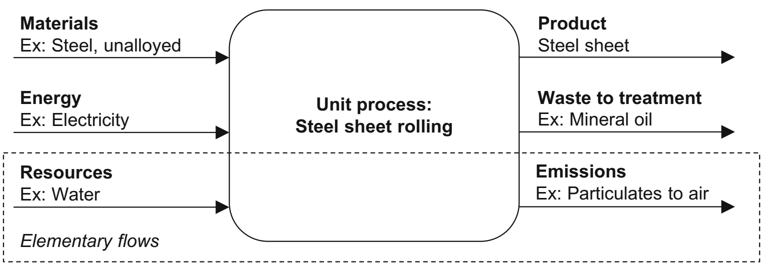

Fig. 8.1 The unit process of steel sheet rolling and examples of flows. The actual unit process contains 86 flows [inspired by: ecoinvent v3 (Weidema et al. 2013)]

as the elementary flow bauxite which contains different minerals, some of which, e.g. $Al(OH)_3$, are sources of aluminium) or cover a group of individual substances (such as the elementary flow VOCs, volatile organic compounds).

What makes resource flows differently from material and energy flows is that they have been “drawn from the ecosphere without previous human transformation”. This means that resource flows are not outputs from other unit processes. In the steel sheet example of Fig. 8.1, the resource flow “water” may be sourced directly from a river close to the location of the steel sheet rolling process (i.e. no previous human transformation), whereas unalloyed steel (a material flow) is the product flow of another unit process and acts as a material flow to the steel sheet rolling unit process. Also, in the example of a unit process composed of an entire slaughterhouse, solar influx may be harvested directly in photovoltaic panels on the roof of the slaughterhouse to produce electricity and the solar influx is then a resource flow to the unit process because it has not undergone a previous human transformation. If the slaughterhouse instead was purchasing electricity from the grid, this electricity would be an energy flow to the slaughterhouse unit process because it has undergone previous human transformation, meaning that it is a product flow of another unit process (e.g. a coal-fired power plant). Similarly, what makes emission flows differently from waste flows is that they are “released into the ecosphere without subsequent human transformation”. This means that emissions are not inputs to other unit processes. In the steel sheet example shown in Fig. 8.1, particulates (emission flow) are emitted directly into the air, whereas mineral oil will go through treatment, i.e. be a material input for another unit process. Chapter 9 will further explain how these concepts are used to model an LCI.

8.2.2 *The Technosphere and the Ecosphere*

LCA divides the world into a technosphere and an ecosphere, see Fig. 8.2.

The *technosphere* can be understood as everything that is intentionally “man-made” and also includes processes that are natural in origin, but manipulated by humans, such as photosynthesis when part of an agricultural system. All unit processes of an LCI model belong to the technosphere.

The *ecosphere* is sometimes referred to as “the environment” or “nature” in layman’s terms and can be understood as everything which is not intentionally “man-made”. In the ecosphere reside those qualities that LCA has been designed to protect, i.e. ecosystems, human health and resource availability. These qualities are called Areas of Protection or damage categories in the field of LCA (see Chap. 10). Changes to the ecosphere can be considered unintentional “man-made” consequences of activities in the technosphere. Note that the ecosphere also undergoes natural changes, for example, via ice age cycles or natural ecological successions, which means that it can be difficult to choose an appropriate natural reference state against which human impacts should be measured, see Chap. 10.

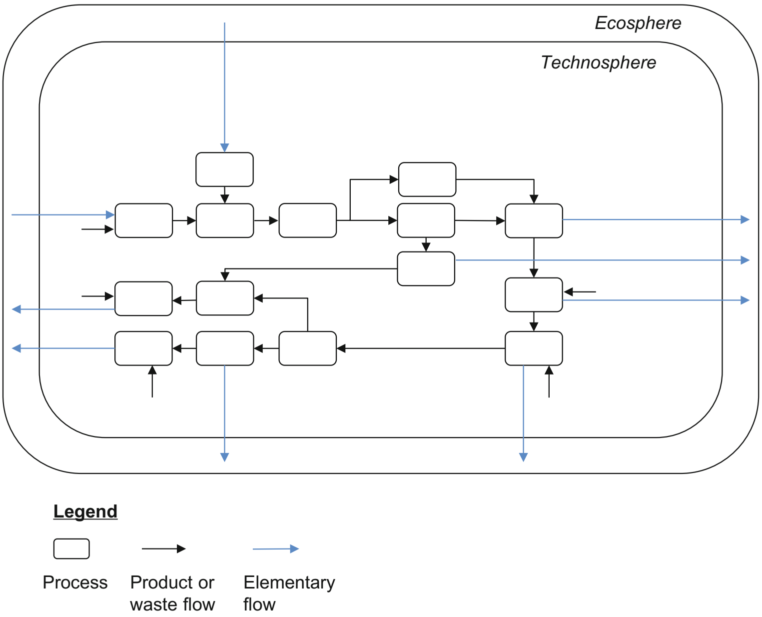

Fig. 8.2 Division between ecosphere and technosphere for a generic product system. Elementary flows are represented by *blue arrows*, while flows within the technosphere are in *black*

Elementary flows are per definition the only flows that go across the boundary between the technosphere and the ecosphere (see Sect. 8.2.1) and it is because of these flows that the Areas of Protections are potentially impacted by the product systems assessed in LCA. Note that there is no clear-cut large-scale spatial separation between the technosphere and the ecosphere. The two spheres are in fact largely intermingled and therefore quite abstract. Surely, natural reserves and undeveloped land largely belong to the ecosphere, but the transportation and tourism infrastructure (roads, trash bins, etc.) going through them belong to the technosphere. In addition, though cities may appear like they belong 100% to the technosphere, the outdoor or indoor air that the population inhales belongs to the ecosphere, because human health can be impacted through air pollution. Note also that the exact location of the boundary between the technosphere and the ecosphere is often debated in the LCA community, for example, with regards to agricultural systems (see Chaps. 29 and 30).

8.2.3 Foreground and Background System

Often hundreds of unit processes are required to deliver the product studied in an LCA. It is useful to distinguish between unit processes belonging to the *foreground*

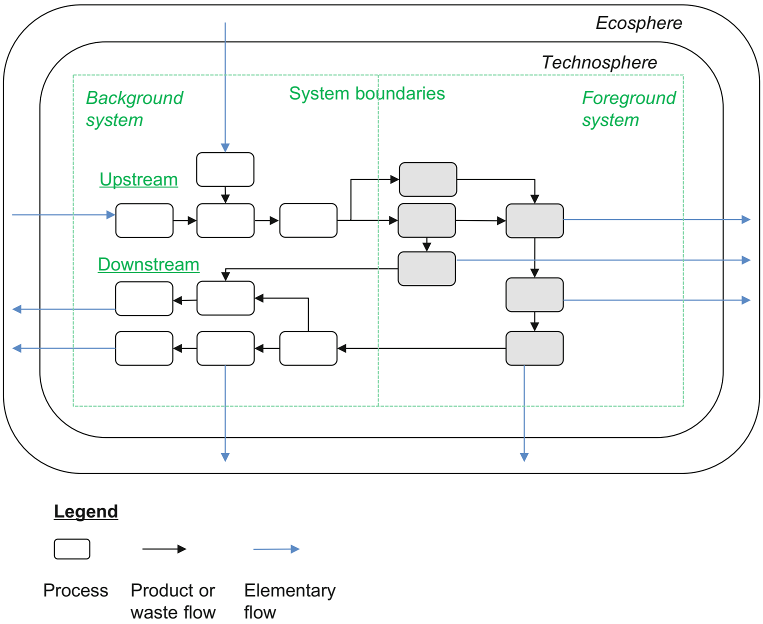

Fig. 8.3 LCI model for the generic product system from Fig. 8.2. The *green box* represents the boundaries of the product system with the division between foreground and background systems indicated. Unit processes with *grey shading* belong to the foreground processes, while unit processes without shading belong to the background system. Part of the background system lies upstream in the value chain and feeds into the foreground system. Another part lies downstream and receives input from the foreground system. *Black arrows* between unit processes indicate material, energy, product or waste flows. *Blue arrows* to and from each unit process represent elementary flows (resources and emissions)

and *background system*. The foreground and background systems are indicated in Fig. 8.3 for a generic product system.

The *foreground system* is commonly defined as comprising those processes of a product system that are specific to it. These processes are in the study of a product typically some of the tier-one suppliers, but may also be suppliers further up the supply chain (e.g. tier-two or tier-three) if these are known by the producer, e.g. through a system of material certification. The foreground system is largely modelled using primary data, i.e. data collected first-hand by the LCA practitioner, e.g. obtained through the commissioner of the study. From a management perspective, processes in the foreground system can often be changed by the decision-maker commissioning a study (e.g. a company), either because they are directly operated by the decision-marker (e.g. at the production site) or because the decision-maker has the power to change or influence the processes, e.g. via purchase decisions or consumer information. In this context, a change can be choosing another supplier (introducing a different unit process in the model) or influencing the way a unit process is operated, thereby changing all or some of its six types of flows qualitatively and quantitatively.

The *background system*, in contrast, is commonly defined as those processes of a system that are not specific to it. Such processes take part in numerous product systems besides the one studied. Examples are society's electricity supply, the production of metallic copper, or the waste management systems. Neither of these is specific to the product under study, but typically purchased in a market without possibility to choose between specified individual suppliers. The background system is typically modelled using LCI databases, which contain average industry data representing the process in specific nations or regions. From a management perspective, processes in the background system can typically not be structurally changed by the decision-maker commissioning a study (e.g. a company), because the decision-maker is only a minor customer and therefore can only exert limited power or because the suppliers are anonymous to the customer like the case of copper which is bought on the global metal market (an exception is Situation B studies where the decision-maker has influencing power on the background system, see Chap. 7). The distinction between foreground and background system is especially useful for planning data collection for the inventory analysis (see Chap. 9) and for making recommendations as part of the interpretation of LCA results (see Chap. 12).

8.2.4 Life Cycle Inventory Model and Results

A life cycle inventory (LCI) model aims to link all unit processes that are required to deliver the product(s) studied in an LCA (glueing together the product system). Figure 8.3 shows an example of an LCI model for a generic product.

An LCI result is an inventory of the aggregated quantities of elementary flows, separated into resources and emissions, from all the unit processes within the system boundary. These elementary flow quantities must be correctly scaled to the assessed product by considering the extent to which the function of each unit process is required to deliver the studied product (see Chap. 9).

8.2.5 Life Cycle Impact Assessment

LCIA is composed of selection of impact categories, classification and characterisation, normalisation and weighting (the latter two are optional steps according to ISO). Chapter 10 details these steps and only their main characteristics and purposes are presented here.

Selection of Impact Categories, Classification and Characterisation

The first step of LCIA involves *selecting the impact categories* that are relevant to consider in the LCA (considering the goal and scope of the study) and *classifying* the elementary flows of the LCI results into these impact categories.

The classification is based on the identification of the environmental issues that each elementary flow can contribute to, such as water depletion, non-renewable resource depletion, climate change or freshwater eutrophication. The purpose of the next step, *characterisation*, is to translate the LCI results (quantities of elementary flows aggregated across all unit processes of an LCI model) into indicator scores for the different impact categories. This essentially reduces a list of hundreds of quantified flows (the LCI results) to a manageable number of indicator scores (typically around 10 or fewer) with a clear environmental meaning, which is practical when comparing the environmental performance of two or more products.

Normalisation

Normalisation is an optional step under ISO 14044:2006 to support the interpretation of the impact profile from the characterisation. Normalisation means that indicator scores for all impact categories are expressed in a common metric, typically the annual contributions to total environmental impacts of an average person. This serves mainly three purposes: (1) for decision-makers to better understand the magnitude of characterised results by relating them to a common familiar and external reference, (2) to check for errors in the assessment resulting in unreasonably low or high normalised results and (3) to pave the road for weighting.

Weighting

Like normalisation, weighting is an optional step under ISO 14044:2006 to support the interpretation of the impact profile. In weighting, the (typically normalised) indicator scores for the different impact categories are made comparable by assigning weights to each impact category that is intended to reflect their relative importance. This relative importance is inherently subjective and can be based on the opinion of experts, policymakers or the general public (or a combination of these). Weighting allows calculating a single indicator score by summing all the weighted impact scores. This is often considered useful by decision-makers wanting to understand which product system performs best "overall" in a comparison.

The detailed choices on impact assessment methods and factors are made in the impact assessment phase of the LCA but it is necessary to select the impact categories in the scoping phase to ensure that the inventory analysis collects data on all elementary flows of potential relevance for the selected impact categories.

8.3 Deliverables

The types of deliverables should directly reflect the intended applications of results, as defined in the goal definition. To be compatible with the ISO 14044 standard an LCA study must include an impact assessment, and most LCA studies have two deliverables, the LCI results and the LCIA results. Some LCA studies (e.g. collection of data for unit process databases) only involve the construction of a life cycle inventory (LCI), in which case the only deliverable is the LCI results. In any case, LCI results should be documented with full transparency (see Sect. 9.7) to ensure reproducibility of the LCA study and potentially allow elements of the underlying LCI model to be used as data sources for other LCA studies, if results are publicly released. LCIA results must be documented by the numerical values of the characterised results for each impact category covered. If normalisation and weighting of characterised results is carried out (see Sect. 8.2.5) the results of these steps must also be documented numerically.

8.4 Object of Assessment

8.4.1 Functions

All LCAs study one or more product systems composed of many unit processes that are active throughout the life cycles of the product system(s). To study these systems the functions they provide must be understood. Indeed, LCA is the environmental assessment of needs fulfilment focusing on functions first and then on the products needed to provide these functions. An LCA study should thus first define the functions from the perspective of the user (later the perspective will change when secondary functions are to be defined, see Sect. 8.5). For example, two different energy technologies may be compared on the basis of the function they provide of enabling the delivery of electricity to households (through a common distribution system). Functions are especially important to understand when comparing two or more product systems because a comparison is only fair and meaningful if the compared systems provide (roughly) the same function(s) to the user. For example, a tablet and a newspaper both provide the function of a news media, but because the tablet provides more functions (access to other websites, word processing and other software) a direct comparison of environmental impacts of a newspaper and a tablet would not be meaningful. An LCA must therefore always be anchored in a precise, quantitative description of the function(s) provided by the analysed product system. In the illustrative case on window frames in Chap. 39, the windows are compared based on their function of allowing daylight into a building.

8.4.2 Functional Unit

To support a fair and relevant quantitative comparison of alternative ways of providing a function, knowledge of the functions provided by the alternative product systems must be used to define a *functional unit*. A functional unit defines the qualitative aspects and quantifies the quantitative aspects of the function, which generally involves answering the questions “what?”, “how much?”, “for how long/how many times?”, “where” and “how well?”. For example, a comparison of outdoor paints may be based on the functional unit: "Complete coverage of 1 m^2 primed outdoor wall for 10 years in Germany in a uniform colour at 99.9% opacity". This is not to say that all LCAs on paint should have this functional unit. In other cases, for example, a particular colour or sheen may be considered an important function and should be included in the functional unit. It is important to understand that the functional unit should always include a function and not simply be a physical quantity, such as 1 kg, 1L or 1 MJ. For example, it would be wrong to compare paints on the basis of a functional unit of "1L paint", since an identical quantity of different paints may deliver different functions, e.g. in terms of area of wall that can be covered, or the quality and duration of the coverage. Figure 8.4 illustrates how this functional unit is composed of answers to the five questions presented above.

It is important to define the functional unit right because it significantly influences the way LCA is performed, its results and interpretation, especially in comparative studies (see Sect. 8.9). This is because the functional unit serves as a reference point for deciding which unit processes to include and to what extent they are drawn upon. It is therefore essential to ensure that the functional unit fully captures the relevant functional aspects of the studied systems. In the following paragraphs, we provide some guidance for defining a correct functional unit.

To get started, two concepts from the product development field are generally useful. These are *obligatory* properties and *positioning* properties. The obligatory properties are features that the product must possess for any user to perceive it as a product (e.g. ability to cover and protect the wall against the weather for an outdoor wall paint) and may also include legally required features (e.g. a car must have seat belts). These can usually be expressed in technical terms. The positioning properties, on the other hand, are optional features of a product, which can be used to position it as more attractive to the consumer in the competition with other similar products. Examples include price, colour, comfort, convenience, image, fashion and aesthetic aspects of the product. Positioning properties often vary from consumer to consumer as opposed to obligatory properties. Tables 8.1 and 8.2 show an example of obligatory and positioning properties for an outdoor wall paint and the window frame case study (Chap. 39), respectively.

After having listed the obligatory and positioning properties they need to be transformed into the functional unit, i.e. they should be used to address the

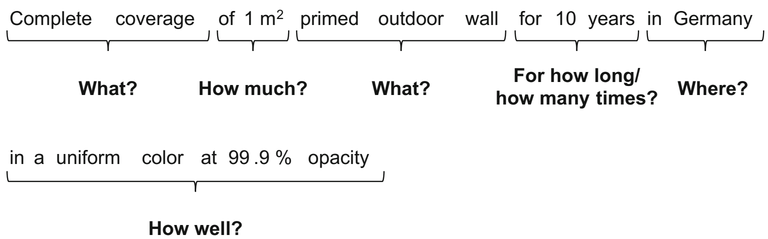

Fig. 8.4 Example of a functional unit composed of five questions

Table 8.1 Derivation of functional unit on the basis of obligatory and positioning properties of an outdoor wall paint

Obligatory properties	Positioning properties
Cover wall with uniform colour Protect wall against rain, sun and microalgae Provide surface that is easy to clean Meet health requirements for application	Drip-free application Many different colour tones to select from Water-based Well covering (needs only one application)
Functional unit Complete coverage of 1 m^2 primed outdoor wall for 10 years in Germany at a uniform colour at 99.9% opacity *Reference flow* 0.67 L of water-based paint A (needs two applications and a re-paint every 2½ years) 0.15 L of water-based paint B (low content of water, only needs one application and lasts 5 years until re-paint is required)	

Table 8.2 Derivation of functional unit on the basis of obligatory and positioning properties of windows

Obligatory properties	Positioning properties
Allow daylight into a building through a physical barrier	Protection from outdoor climate (thermal and noise insulation) Allow ventilation between indoor and outdoor Provide aesthetic functionality to the building Protection against breaking into the building
Functional unit Allow daylight into a building through a physical barrier, equivalent to light being transmitted through an area of 1.23×1.48 m^2 with visible light transmittance of at least 0.7, for 20 years *Reference flow* 0.5–0.67 window frames, depending on material 1 window pane Paint for maintaining surface of window pane (dependent on frame material)	

questions “what?”, “how much?”, “for how long/how many times?”, “where” and “how well?”, as in the example of Fig. 8.4. When defining the functional unit it is useful to distinguish between its quantitative and qualitative aspects.

The *quantitative* aspects always make up the answers to the “how much?” and “for how long/how many times?” questions and often take part of the answer to the “how well?” question. In the example of an LCA on shopping bags quantitative functional aspects may be the volume (“how much?”), the number of shopping trips that the bag should be used for (“how long/many times?”) and strength, i.e. the weight that can be carried (“how well?”). For products that are continually in use (e.g. a fridge or a paint) the “how long/many times?” question should be addressed in the form of the time during which the product is in function (as in the paint example of Fig. 8.4). For products that are not in use all the time (e.g. clothes, mobile phones) the “how long/many times?” question should instead be addressed by specifying the intensity of the use, either as the total duration of use (e.g. 1000 h) or the number of times that the function is provided (e.g. 50 shopping trips for the shopping back example above). In the window frame case study the “how well?” question was partly addressed quantitatively by defining a visible light transmittance (the fraction of light that a window allows into the building) of at least 0.7 in the functional unit. The magnitude of the quantitative aspects in the functional unit can be chosen more or less arbitrarily. However, for the users of an LCA, it often makes the most sense to relate it to the magnitudes of typical use by a person, a family or a community. In the example of Fig. 8.4 it would be less intuitive to relate to a functional unit involving the complete coverage of 1 km^2 primed outdoor wall, while a good magnitude in the functional unit for a study of waste incinerators could be the household waste generated by the municipality in one year.

The *qualitative* aspects cover the way in which the function is provided and are often not easily quantifiable and sometimes not even clear-cut. The “what?” and “where” questions require qualitative answers. In the example of Fig. 8.4 the “what?” question is answered by “complete coverage of primed outdoor wall” and the “where?” question by “Germany”. Other qualitative aspects are often used to answer the “how well?” question. These could be legal requirements, e.g. fire safety measures in a car or an office building, or technical standards, e.g. RAL code 3020 for the colour of paint. References to relevant legal requirements and technical standards in the functional unit are helpful, because they ensure comparability through adherence to the standard. To fully address the “how well?” question subjective or ambiguous elements related to user perception (e.g. fashion) are often important to include, to ensure comparability of different products. For example, products may be discarded by users although they still fulfil their technical functions because they are no longer perceived as fashionable. For this reason, it is important to understand which aspects of a studied product’s function, including non-technical aspects such as fashion, that are perceived as important by users. LCA practitioners carrying out a study are therefore advised to consult the users of the product or service that is studied to ensure that the definition of the functional unit captures their perception of the product’s functionality. Those non-technical aspects that differ between compared products should either be included in the functional unit or considered separately in the interpretation phase of the LCA (see Chap. 12).

The authors of this chapter have over the years encountered many types of mistakes in the definition of functional units. Box 8.1 provides selected examples of such mistakes and explains what is wrong with them and what needs to be considered to prevent making them.

Box 8.1: Common Types of Mistakes when Defining the Functional Unit

1. **Assuming that same physical quantity of product equals the same function**:

Example: “1 kg of packaging material”

Explanation: A physical quantity, such as mass, is not a function. The mass required to provide a packaging function often depends on the material.

As an example, glass and PET in beverage packaging have different densities and physical properties, and different masses will therefore be required for providing the same function. To prevent mistakes like this, the functionality of the product should be considered (for example, what is the functionality of packaging?).

2. **Being overly restrictive**:

Example: "Enable watching of television with a 30 W power consumption for 10,000 h"

Explanation: A fixed power consumption is (except in special cases) not relevant to the user of a television and means that only televisions with that exact power consumption can be included in a study. To prevent mistakes like this, it must be ensured that the functional unit only covers what relates to the function of the product (to watch television).

3. **Incorrect use of technical standards or legal requirements**:

Example: "Driving 1000 average person-kilometres in a diesel passenger car that fulfils the Euro 6 standard and therefore emitting less than 0.08 g NO_X per kilometre (Euro 6 standard) during use"

Explanation: Often products can demonstrate compliance with the law or a voluntary standard when completing a test that does not represent the actual conditions of the product's use. A passenger car complying with the Euro 6 standard may emit more NO_X than 0.08 g/km, depending on the driving pattern, climate, etc. A misinterpretation of a technical standard in the functional unit can therefore lead to mistakes in the LCI (in this case, underestimated NO_X emissions). To prevent mistakes like this, the condition of the use must be considered. Generally, a reference to a technical standard in the functional unit does not need to be accompanied by the exact meaning of the technical standard, as this will be dealt with in the LCI modelling step.

It must be stressed that a solid insight in the relevant technological domain is required to define a meaningful functional unit. For example, good knowledge about biofuels, nanomaterials or remediation of contaminated sites is required to define meaningful functional units for these technologies. Chapters 26–36 discuss the application of LCA, including the definition of functional units, for a wide range of technological domains.

8.4.3 Reference Flows

When the functional unit has been defined, the *reference flows* can be determined. A reference flow is the product flow to which all input and output flows for the processes in the product system must be quantitatively related. In other words, the reference flow is the amount of product that is needed to realise the functional unit. For example, as shown in Table 8.1, 0.67 L of paint A is required to realise the functional unit in Fig. 8.4, while the same functional unit is realised with 0.15 L of paint B. The reference flow is typically different qualitatively and quantitatively for different products compared on the basis of a functional unit, due to differences in product properties and characteristics (e.g. viscosity and tear resistance of a paint). The reference flow is the starting point for the ensuing LCI analysis phase of an LCA (see Chap. 9), because it determines all the product flows required throughout the life cycle of the product system studied and their associated elementary flows (resource uses and emissions). It is very important not to confuse a reference flow with a functional unit (see Example 1 in Box 8.1). The former can only be known when the latter is correctly defined. One should, for example, never base an LCA on the comparison of 1 L of two different paints, unless a correctly defined functional unit has shown that the reference flows of the compared paints are quantitatively identical. It is important to understand the use situation in order to correctly define reference flows. For example, to define reference flows in a comparison of a disposable cardboard cup and a ceramic cup, the LCA practitioner must understand the number of times the two cups are used before they are discarded and how the ceramic cup is cleaned (by hand or dishwasher, and the associated consumption of detergent and water and its temperature). Tables 8.1 and 8.2 include functional unit and corresponding reference flows for the example of outdoor wall paint and the window frame case study (Chap. 39), respectively.

8.5 LCI Modelling Framework and Handling of Multifunctional Processes

This part of the scope definition deals with the choice of an appropriate LCI modelling framework and ways to handle multifunctional processes. These choices must be made in accordance with the goal definition, particularly the identified decision context (Situation A, B or C, see Sect. 7.3), and they have a strong influence on the inventory analysis, the LCA results and their interpretation.

8.5.1 Secondary Functions and Multifunctional Processes

To understand why different LCI modelling frameworks exist we first need to consider that a product system often delivers other types of function than the type dealt with in Tables 8.1 and 8.2. The functions of Tables 8.1 and 8.2 all relate to obligatory or positioning properties and are intended functions made available to product users by, e.g. companies selling the products. They are called *primary functions*. In addition to those, *secondary functions* can also emerge in the life cycle of a product system. Secondary functions are unintended functions that usually have low or no relevance to the users of a product, meaning that they are not contributing to the obligatory or positioning properties. Instead, secondary functions are relevant to other systems of the technosphere that the studied product system interacts with. The existence of secondary functions reflects the fact that some processes are *multifunctional*. A process is multifunctional when it provides more than one function, meaning that it either delivers more than one product output and/or provides more than one service. An example of a multifunctional process that delivers more than one product output is animal husbandry where the cow may deliver both milk, meat, hide, bone meal and other products with an economic value. The production of the hide is an example of a secondary function of the husbandry from the perspective of the user of a bottle of milk, since hide is neither an obligatory nor a positioning property of the milk. An example of a multifunctional process that both deliver more than one product output and provide more than one service is waste incineration. It provides the multiple services of getting rid of many different types of wastes (the obligatory property) and can deliver both electricity and heat while doing so. Thus, secondary functions of a product that is disposed of by incineration are the production of heat and electricity. These secondary functions are relevant from the perspective of the energy system that the product system interact with because a change in the volume of discarded products that is incinerated leads to a change in the amount of energy generated from incineration.

Multifunctional processes constitute a methodological challenge in LCA, which is based on the idea of analysing individual product systems based on the primary functions they provide in order to determine the environmental impact from the product. In the real world, there is hardly any product system that exists in isolation. As soon as a by-product arises from a multifunctional process (e.g. animal husbandry), it is economic common sense to try to utilise it, often in a different context from the product system being analysed in the LCA. This means that the process becomes part of another product system as well, and that the environmental impacts from the process can no longer be fully ascribed to the product system studied.

8.5.2 The ISO 14044 Hierarchy to Solving Multifunctionality

In order to solve multifunctionality issues, the ISO 14044 standard presents a hierarchy of solutions. These solutions can both be used to make different product systems functionally comparable and to represent a single product system in a hotspot analysis. The levels of the hierarchy are presented below and the hierarchy is summarised as a decision tree in Fig. 8.5. Chapter 9 shows how to use to ISO hierarchy in practice when constructing an LCI.

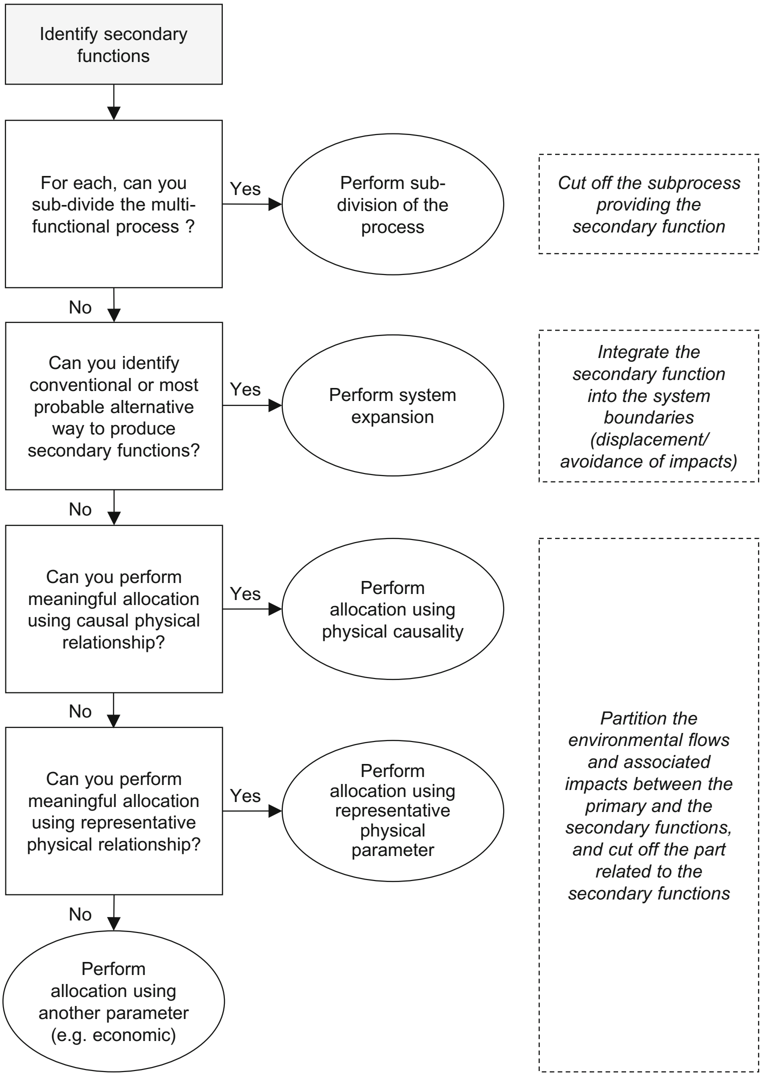

Fig. 8.5 ISO hierarchy for solving multifunctionality presented in a decision tree

Subdivision of Unit Process

First choice is to try to solve this problem through increasing the resolution of the modelling by dividing the multifunctional unit process into minor units to see whether it is possible in this way to separate the production of the product from the production of the co-product, and if so exclude the subprocesses that provide the additional functions from the product system, see Fig. 8.6.

An example of subdivision is when a factory produces two products. Here, the subdivision approach may lead to the realisation that the factory actually contains a

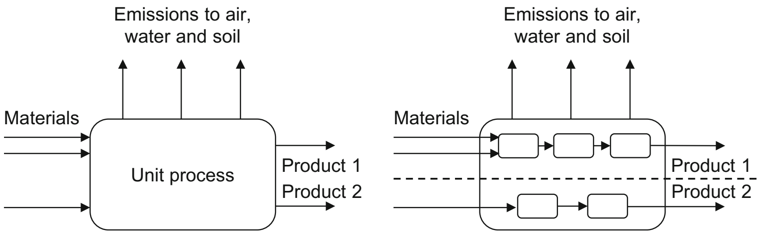

Fig. 8.6 Solving the multifunctionality problem by increasing the modelling resolution and sub-dividing the process into minor units which can unambiguously be assigned to either of the functional outputs

number of processes and that the processes needed for the production of the first product are physically separated from the processes needed for the production of the second product. This approach to solving multifunctionality does not always work. Even if you zoom to the molecular level of a cow, it is not possible to physically separate the metabolic processes in the cow that lead to the production of milk from the ones that lead to the production of meat or hide.

System Expansion

If subdivision fails to solve the multifunctionality problem, the ISO standard recommends trying to solve the problem by system expansion. In a comparison of two processes, this means expanding the second process with the most likely alternative way of providing the secondary function of the first process. In the comparison of power plant 1, which has district heating with co-generated heat as a secondary function, with a power plant 2, which only produces electricity, this means expanding the system of plant 2 with the most likely alternative way or combination of ways of providing district heat in that region (see Fig. 8.7).

Expansion of system 2 with the alternative way to produce the secondary function of system 1 is equivalent to subtracting the alternative way from system 1 (which provides the function). This is also called to credit system 1 with the inputs and outputs which are avoided when its secondary service replaces this alternative production. In the case of district heating being the secondary function, system expansion would thus be the same as crediting the power plant, which produces the district heat, through subtracting the impacts from the most likely alternative way of producing this heat as illustrated in Fig. 8.6.

In Fig. 8.6 equation B follows from equation A by subtraction of the alternative way of district heating from both sides of the equal sign. The approach of system expansion is thus mathematically equivalent to crediting for avoided production. Crediting for avoided production is typically used to account for secondary functions in a hotspot analysis where there is not a comparison of two alternative systems. For example, a product system that includes incineration can be credited for the avoided impacts from the production of heat and electricity by subtracting the avoided elementary flows in the inventory of the process (see Chap. 9 for technical details). In the milk example, system expansion can be performed by

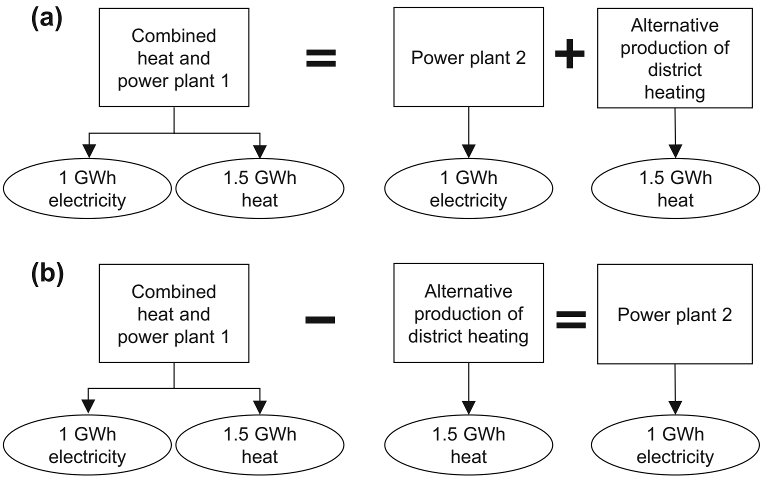

Fig. 8.7 Equivalent modelling approach when dealing with multifunctionality. **a** System expansion: to ensure equal functionality system 2 is expanded to include the secondary function of system 1. **b** Crediting: system 1 is credited for the production of the secondary function, in order to have equal functionality of system 2

crediting the milk for the avoided impacts from alternative production of beef and other co-products. This alternative production might be the raising of cattle in a pure beef production system (which includes hides and other low-value co-products). Note that quality differences between dairy cow meat and cattle meat means that they may not be functionally equivalent. This may require the application of a value correction factor to the crediting.

An important task in system expansion is to identify the process (or combination of processes) which is superseded by the co-product. This relates to the decision context (Situation A, B or C1/C2) identified in the goal definition (Sect. 7.4) and will be dealt with in Sect. 8.5.3.

Allocation

Sometimes it is not feasible to obtain complete functional equivalency between the compared systems or to isolate the primary function of a process from the secondary functions through system expansion. This may be the case when there is no alternative way to produce the secondary functions. A classic example of such a multi-output process is a petrochemical refinery with a variety of different organic substances as output without any mainstream alternative routes of production for these. It may also be the case when the most likely alternative route also has secondary functions, creating the need for further system expansion introducing alternative routes for the new level of secondary functions, which again may have secondary functions, creating the need for further system expansion and so on. In the milk example, the alternative production of meat from raising of cattle for example leads to the co-production of horn (for example used in jewellery production), which cannot be produced in isolation and for which there may not exist a functionally equivalent material.

When system expansion is not feasible, or when it is in conflict with the goal definition (for Situation C2, see below), the ISO 14044 standard recommends dividing the inputs and outputs of the multifunctional process or system between the different products or functions. This is called allocation.

If possible, the allocation should be performed in accordance with the underlying causal physical relationships between the different products or functions, reflecting the way in which the input and output quantities are affected by changes in the quantities of products or functions delivered by the process or system. For example, in the hypothetical example of a waste incineration plant that incinerates two waste inputs, batteries and plastic, emissions of the toxic metal cadmium from the process will originate entirely from the batteries, given that the plastic stream contains no cadmium and that cadmium cannot be formed in the waste incineration process. This conclusion on the origin of cadmium, based on deductive reasoning, could also have been reached empirically by measuring changes in cadmium emissions in response to changes in waste inputs (e.g. a doubling of cadmium emissions would be expected from a doubling of battery inputs). A causal physical relationship can thus be established and cadmium emissions can be allocated 100% to the batteries. In the case of the milk example, the International Dairy Association recommends that physical allocation be based on the different physiological feed requirements for an animal to produce milk and meat (IDF 2010). In the absence of a causal physical relationship between the products, the ISO standard recommends performing the allocation according to representative parameters. This is possible when co-products provide identical or similar functions. In the case of a waste incineration plant that delivers both heat and electricity as output, the exergy content of the two flows may, depending on the study context, be used as a representative physical parameter or allocation key, because it reflects the potential of each energyform to perform mechanical work. Here, it is important that the representative physical parameter actually represents a common function of the co-products. In the example of an agricultural process that produces both wheat and straw, the energy content of the two flows can only be used as a representative parameter if they are both intended as animal fodder (a common function). If instead, the wheat is intended as food for humans this choice of representative parameter would be wrong (food for humans deliver many more functions than energy, e.g. vitamins and taste).

When no common representative physical parameter can be identified for the different outputs, another relationship must be found between them. As an example, the ISO standard mentions an economic relationship, and indeed, this is a frequently applied allocation parameter. In economic allocation the inputs and outputs of the process or system are divided between its products according to their respective economic values, e.g. determined as their long-term average market prices, or some shadow price in cases where there is no market, e.g. for intermediary products. A justification for the use of economic allocation is that products are produced due to an incentive of financial income, and that a co-product with a market value close to 0 should be allocated a correspondingly low share of the non-product flows of a process, compared to a primary product with a high market value. In the extreme situation where the value of the co-product is zero, its allocated share of the inputs and outputs also becomes zero in accordance with the fact that a zero-value output is not a co-product but waste and should be modelled as such.

8.5.3 LCI Modelling Framework: Attributional and Consequential LCA

Traditionally, there have been two main LCI modelling frameworks: *attributional* and *consequential* modelling. In the ILCD guidelines, these were adapted to match the four decision context situations (i.e. A, B, C1 and C2). Understanding the difference between attributional and consequential modelling and when to use what has been one of the most difficult aspects of LCA, and there is still no consensus on this issue within the LCA community. In addition, some aspects of the terminology defined in the ILCD guidelines, in particular with regard to the definition and settings of attributional modelling, are inconsistent with the traditional views within the LCA community, thus adding more confusion to the matter (Ekvall et al. 2016). Below we first offer an explanation of the two modelling frameworks, including their handling of multifunctional processes and the use of average or so-called marginal LCI data (to be explained below). Where relevant we specify discrepancies between the ILCD guidelines and the traditional views. Table 8.3 summarises the explanation and discrepancies. We then provide guidance in compliance with the ILCD guidelines for selecting the LCI modelling framework with consideration to the goal definition.

Attributional LCI modelling was initially the common practice when LCA development caught pace in the early-mid nineties. The overall aim of attributional modelling is to represent a product system in isolation from the rest of the technosphere or economy. The question addressed by attributional LCA can be said to

Table 8.3 The meaning of the attributional and consequential modelling frameworks and their handling of multifunctionality

LCI modelling framework	Question to be answered	Handling of multifunctional processes when subdivision is not possible		Modelling of background system
		Before ILCD	ILCD	
Attributional	What environmental impact can be attributed to product X?	Allocation	System expansion or allocation	Average processes
Consequential	What are the environmental consequences of consuming X?	System expansion	System expansion	Marginal processes

be “what environmental impact can be *attributed* to product X?” or “what environmental impact is product X *responsible* for?” As hinted by these questions, there is an element of subjectivity involved in attributing impacts to a product system or deciding the impact responsibility of a product system. This subjectivity arises in the act of artificially separating the studied product system from the rest of the economy. This separation is artificial because many, if not most, product systems interact with other products systems through multifunctional processes, meaning that they, as explained in the previous section, cannot be described as physical entities in isolation. For example, from a strict physical perspective, the product system of a bottle of milk cannot be described in isolation and the assignment of processes that the product system is seen as “responsible for” therefore involves choices. Before the ILCD guidelines came into place attributional modelling was generally associated with allocation as the approach to solving the issue of multifunctional processes, provided that subdivision (the preferred solution of the ISO hierarchy) was not possible. By contrast, ILCD in some cases recommends solving multifunctionality by system expansion within an attributional modelling framework (see below).

Besides the issue of multifunctionality, attributional LCA is also associated with the use of average processes in the background system, which reflects the modelling of an average supply chain. In practice, this means that a market mix is used. This could be for the global aluminium market or the electricitymarket of a nation. The former is composed of a range of bauxite mines with different ore grades and processing facilities that employ different production technologies, while the latter is composed of different energy conversion technologies, such as the combustion of coal, natural gas, oil and biomass, the harvesting of wind and solar power and the use of nuclear power. As an example, Fig. 8.8 shows the Danish electricity consumption mix in 2014.

Consequential LCI modelling was developed around the year 2000 to eliminate the weakness inherent in the attributional LCA modelling framework due to the attempt to artificially separate a product from the rest of the economy. Its overall aim is to describe the changes to the economy caused by the introduction of the studied product system, i.e. the product system’s consequence. Consequential LCI modelling thus aims to answer the question “*What are the environmental consequences of consuming X?*” For example, a consequential LCA of a bottle of milk would attempt to model how the market responds to the change in demand for milk represented by the functional unit of the study (e.g. involving a milk volume of 1 L or a specified nutritional value). This is a very different approach than attributional modelling because the change in the economy can look very different than the representation of the isolated bottle of milk system. For example, the increased demand for milk may lead to an increase in the capacity for milk production (i.e. the numbers of cows giving milk), which in turn may lead to a reduction in the production of some meat (e.g. beef from raising cattle) due to the increasing supply of meat from dairy cows. This corresponds to handling the multifunctional process of milk production by system expansion. A consequence of increased consumption of milk may therefore be a reduction in environmental impacts from the avoided

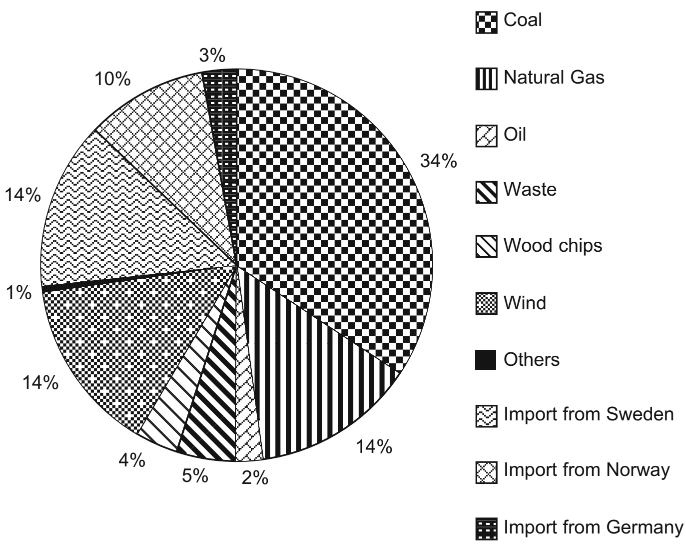

Fig. 8.8 Danish electricity consumption mix in 2014 (low voltage, e.g. for domestic consumption). Imports from neighbouring countries can be further broken down into energy sources (Treyer and Bauer 2013)

production of beef from cattle, which is somewhat counterintuitive. The market may also be influenced by an increased demand for a product in other cases than multifunctionality. For example, if an additional kg is demanded of a fish species that is already fished at its maximum level permitted by regulation (a production constraint) a consequence may be an increase in the production of another protein source that is not constrained, such as chicken, and the environmental impacts following this increase. The examples show that consequential modelling to a large extent relies on a good understanding of and ability to model the dynamics of the economic system, which requires a markedly different way of thinking than the engineering perspective on product supply chains that historically has been in the core of LCA (see Chap. 3).

Contrary to attributional LCA, consequential LCA is not associated with the use of average processes for modelling the background system, but instead with the use of marginal processes. These are the processes that are employed or taken out of use as a response to an increase or decrease in the demand for a product, respectively. In the example of the Danish electricity system, the short-term marginal process will never be solar or wind, because solar irradiance or the wind are natural processes that cannot be "turned up or down" in response to a short-term change in electricity demand. Instead, the short-term marginal process in this example is a combustion process because it is possible to quickly adjust the rate at which something (e.g. coal or natural gas) is combusted in response to a change in electricity demand. The short-term marginal is often the combustion of natural gas, because this is a more expensive way of generating electricity than coal and thus sensitive to changes in electricity prices caused by changes in electricity demand (often, natural gas is only used during peak demand when a relatively high electricity price makes this technology economically viable). However, the relevant marginal processes to include in an LCI model are not always the ones that are affected as an immediate consequence of a decision, i.e. short-term marginal processes. Long-term marginal processes may be more relevant if a decision leads to large changes in supply or demand. Long-term marginal processes represent changes in the installed production capacity in response to the projected development of electricity demand. Often it is difficult to identify a single long-term marginal process, which is why a mix of potential long-term marginal processes is often used. Figure 8.9 shows such a mix for the long-term marginal electricity technology in the Danish market. See Chap. 9 on the identification of short- and long-term marginal processes.

It can be seen that fewer electricity production processes are part of the mix in Fig. 8.9 for consequential modelling than the mix in Fig. 8.8 for attributional modelling. For example, waste as an electricity source is not part of the consequential mix and this is because the long-term planning of waste incineration is thought to consider projections in future waste volumes (the primary function of waste incineration is to "get rid of" solid waste) rather than projections in future electricity demand. On the other hand, the construction of new wind turbines and coal-fired power plants (and to a very small extent, hydropower plants and rooftop photovoltaic panels) are thought to consider projections in future Danish electricity demand. When to consider short- versus long-term marginal processes in consequential LCA and how to identify these are still being debated in the LCA community.

Note that while the background system is modelled differently in attributional and consequential LCA, the foreground system is overall modelled in the same way, the only exception being the handling of multifunctional processes.

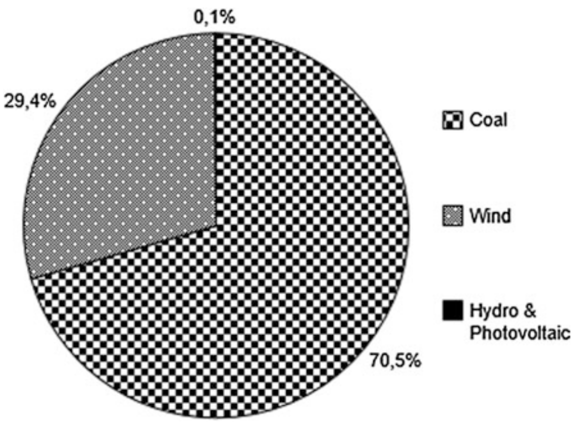

Fig. 8.9 Danish market mix of long-term marginal electricity processes (low voltage, e.g. for domestic consumption) (Treyer and Bauer 2013)

8.5.4 Recommended Modelling Choices for the Identified Decision Context

ILCD provides recommendations for model choices for each of decision contexts (Situation A, B, C1 and C2) identified as part of the goal definition (see Chap. 7). These recommendations are the outcome of a comprehensive consultation process within the LCA community. Since different actors with different views have had a saying in this consensus process leading up to the ILCD recommendations, they are somewhat internally inconsistent, as pointed out by, for example, Ekvall et al. (2016). Below we present the recommendations for each decision context and make notes about the parts that are disputed. Table 8.4 summarises the recommendations.

Situation A

Situation A concerns micro-level decision support (see Chap. 7) and the consequence of a decision (e.g. the introduction of a new product on the market) is therefore of interest. Ideally, the marginal process should therefore be identified and used for all background processes (such as electricity supply) and cases of multi-functionality (e.g. of an incineration process) should be handled by system expansion with marginal processes, provided that subdivision is not possible (see Sect. 8.5.2). This ideal for Situation A is logically consistent with a consequential modelling framework. Yet, ILCD recommends using an average market consumption mix for background processes and in cases of system expansion in the background system. ILCD terms this attributional modelling, although system expansion was previously associated with consequential modelling, as mentioned above. The main reason for diverging from the ideal is that for the small changes studied under Situation A it can be very difficult to identify marginal processes, i.e. to understand the long- and short-term consequences on the market of introducing a small change in its composition of product systems. The actual market behaviour in response to small changes may also not be well-represented by simple mathematical

Table 8.4 Summary of ILCD recommendations on LCI modelling choices

Decision context	LCI modelling framework (ILCD terminology)	Handling of multifunctional processes when subdivision is not possible	Modelling of background system
Situation A	Attributional	System expansion	Average processes
Situation B	Mix of attributional and consequential	System expansion	Mix of long-term marginal processes for processes structurally changed. Average processes in all other cases
Situation C1	Attributional	System expansion	Average processes
Situation C2	Attributional	Allocation	Average processes

equations, which makes it difficult to model what will actually happen, short-term and long-term, when, for example, a light-bulb is turned on, compared to a situation where it is not turned on. There is therefore a risk of using wrong marginal processes and this is problematic because LCA results are often quite sensitive to the choices of marginal process (e.g. natural gas vs. wind for electricity supply). These considerations have lead ILCD to pragmatically recommend using average processes in the background system. It must be mentioned that some LCA experts prefer to pursue the ideal by using marginal processes in Situation A studies, which conflicts with the presented ILCD recommendations.

Situation B

Situation B concerns meso/macro-level decision support (see Chap. 7). ILCD recommends the same modelling choices as for Situation A, with the exception that background processes in the studied product system that have been identified as being affected by structural changes as consequence of the analysed decision are recommended to be modelled as mix of the long-term marginal processes. The logic behind this exception is that marginal processes for suppliers that experience structural changes are easier to identify than marginal processes for suppliers that just experience changes in terms of the volume of products they deliver. The reason for the focus on the long-term marginal is that the consequences studied under Situation B are generally long term. Still, identifying the correct long-term marginal processes in Situation B can be challenging and this is why it is pragmatically recommended to use a mix of possible long-term marginal processes, rather than actual long-term marginal processes, such as the mix for electricity shown in Fig. 8.9. Chapter 9 addresses the calculation of such a mix. In light of the uncertainty involved, we advise to model the LCI using a range of different mixes to analyse how sensitive results are to the estimated mix (see Chap. 12). As for Situation A studies, some LCA experts prefer to pursue the ideal of using a fully consequential approach by only using marginal processes (either single process or a mix) in Situation B studies, which conflicts with the presented ILCD recommendations.

Situation C

Situation C relates to accounting, meaning that studies are not to be used to directly support decisions and are of purely descriptive nature, often describing what has already happened. Situation C1 considers interactions with other systems and ILCD recommends handling this interaction via system expansion (for solving multi-functional processes where subdivision is not possible) and use of average processes in the background system. This means that the recommendations of ILCD in practice are similar for Situation A and C1, even though the modelling ideals of Situation A and C1 are different. Situation C2 disregards interactions with other systems and ILCD therefore recommends that allocation be systematically used to solve multifunctional processes, provided that subdivision is not possible. Note that this conflicts with the ISO hierarchy, according to which system expansion should be performed when possible instead of allocation.

8.6 System Boundaries and Completeness Requirements

System boundaries demarcate the boundaries between the studied product system and (1) the surrounding economy (technosphere) and (2) the environment (ecosphere). "Completeness requirements" is a related concept that can be used to determine what processes should be included within the system boundaries to reach the degree of completeness in the product system modelling that is needed to be in agreement with the goal of a study (see details below). The setting of the system boundaries can have a large influence on LCA results because they determine the unit processes from which environmental impacts should be quantified. At this point in the scope definition, the system boundaries should be represented in a diagram that provides an overview of which parts of the studied product system(s) that are included and which are excluded. An appropriate level of detail in this diagram is the life cycle stages (such as production, manufacturing, transportation, retail, use and disposal) or the main processing steps. It is often useful to start with the process or life cycle stage that delivers the reference flow and then expand upstream and downstream. See Fig. 8.10 for an example diagram for the study of a steel sheet used to prevent accidents during roadworks. Note that the diagram does not need to contain individual unit processes, as this full level of detail will only be achieved in the actual construction of the inventory model (Chap. 9).

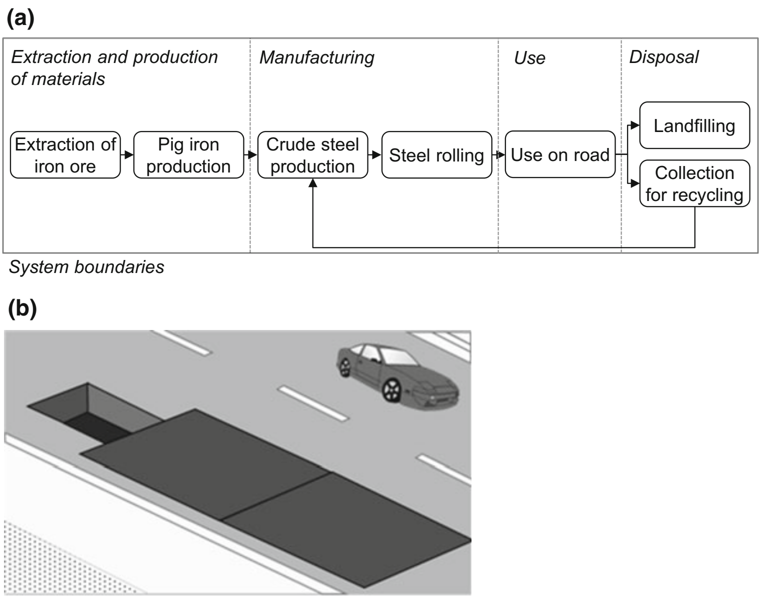

Fig. 8.10 **a** Example of system boundaries diagram for the life cycle of a steel sheet used to prevent accidents during roadworks. Only the main process steps in the life cycle are shown. **b** Illustration of steel sheets in use

8.6.1 Ideal System Boundaries

Ideally, within the system boundaries should be all the unit processes required to deliver the reference flow(s) defined by the functional unit. In cases where multi-functionality is handled by system expansion, this also includes processes from other systems that interact with the studied system. System boundaries should ideally be set so that all flows crossing them are elementary flows (resources and emissions). In other words, no material, energy, product or waste to treatment flows should cross the system boundaries. Ideal system boundaries thereby contain all the unit processes used to deliver the reference flow(s) by (1) generating energy and products (materials for other unit processes) from extracted resources and (2) treating waste flows to the point where the only outputs are emissions. Figure 8.11 illustrates an ideal system boundary for a simple hypothetical product system containing just fifteen unit processes. In this case, the inventory model is fully complete, because all unit processes needed to deliver the reference flows are inside the system boundaries.

Outside the system boundaries lies the rest of the *technosphere* (not shown in Fig. 8.9), i.e. the total body of other product systems in the global economy, and the *ecosphere*, i.e. which is affected by resource uses and emissions from the technosphere.

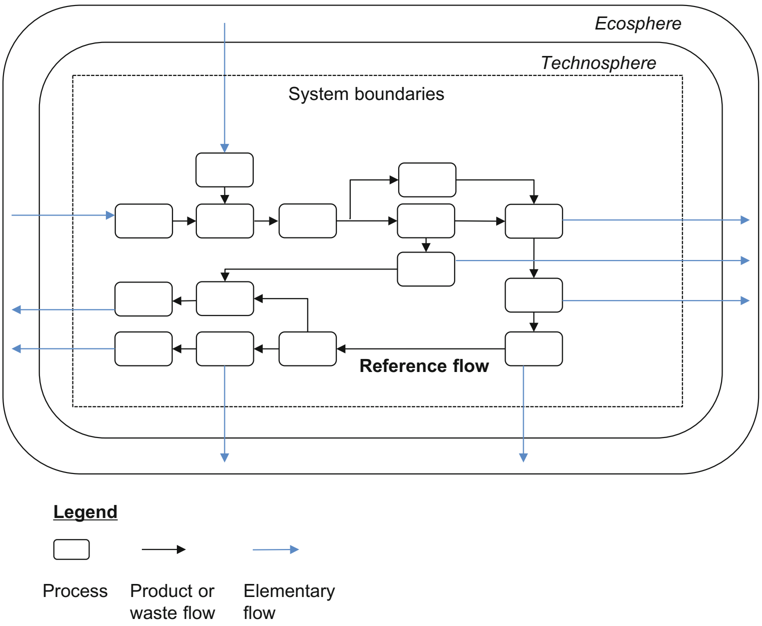

Fig. 8.11 Setting of system boundaries for a simple hypothetical product system. The boundary contains all the unit processes required to deliver the reference flow (*bold*), and the only flows crossing the system boundaries are elementary flows (*blue*). Note that the rest of the technosphere is not shown

8.6.2 Reasons to Divert from Ideal System Boundaries

There are three reasons to divert from working with ideal system boundaries:

First, if a study does not take a full life cycle perspective the rule of only allowing elementary flows to cross the system boundary does not apply. A study taking a full life cycle perspective aims to cover all the processes that are needed to deliver the function(s) of interest upstream (extraction and production of raw materials and manufacturing) and downstream (disposal) to the use stage. By contrast, a so-called “cradle-to-gate” study is an example of a study not taking a full life cycle perspective because the system boundary ends at the gate of the factory where the studied product is produced. In this case, the product flow thus crosses the system boundary, as shown in Fig. 8.12 (based on the simple hypothetical product system shown in Fig. 8.11). The goal definition’s intended applications of results decides whether a full life cycle perspective should be taken (see Chap. 7). This decision is usually also reflected by the functional unit (see Sect. 8.4.2).

Second, in comparative studies it is justified to exclude identical processes if they deliver identical quantities of services (energy, materials or treatment of waste) in the systems studied. For example, in the illustrative case study on window frames (Chap. 39) comparing four windows, the processes involved in cleaning the

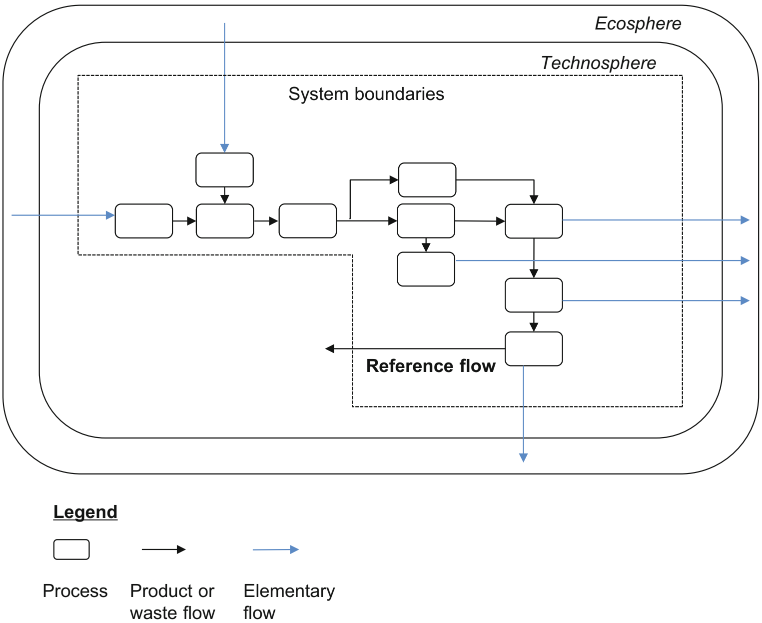

Fig. 8.12 Setting of system boundaries for a simple hypothetical product system in a cradle-to-gate assessment. In this case, the reference flow (*bold*) is crossing the system boundaries, to the rest of the technosphere; in addition to the elementary flows (*blue*) entering or leaving the ecosphere

windows throughout their use stages were excluded from the system of each window because users are expected to clean the windows, that all have the same surface area, in the same way, using the same amount of water and detergent. While this kind of exclusion is allowed for comparisons between systems, it prevents a proper hotspot analysis because it is unknown how much the omitted processes contribute to overall environmental impacts.

Third, constructing an LCI model with ideal boundaries is practically impossible. This is because the number of unit processes actually required to deliver a reference flow is often, even for simple products, enormous: Typically, unit processes require around 5–10 material or energy inputs that each needs to be produced by a unit process that in itself requires around 5–10 material or energy inputs, etc. Furthermore, many product systems include examples of infinite loops where one process A requires input from another process B to deliver an output that is needed by process B to produce the input to process A. Every step back in a value chain represents a step back in time and ideal system boundaries would therefore need to encompass a large part of industrial history, which is not practically possible to model. Yet, amongst the enormous number of unit processes that should ideally be included in the system boundaries, only a minority actually have a quantitatively relevant contribution to the environmental impacts of the studied product system. For example, the ballpoint pens used by employees at a coal-fired power plant obviously have an insignificant contribution to the environmental impacts of a unit of power generation.

Therefore, all LCA studies in practice cut-off some unit processes that are actually needed (although to a very limited extent) to deliver the reference flow. This presents a dilemma of the system scoping. You should include within your system boundaries the processes that matter, i.e. contribute significantly to the overall impacts from the product system, but how can you determine whether a process matters before you know what the total impacts are and can relate the impacts from the process to this number? The solution to this dilemma lies in the iterative approach to LCA that was introduced in Sect. 6.3 and presented for inventory modelling in Sect. 9.3. Figure 8.13 shows examples of excluded product flows.

8.6.3 Completeness Requirements: Quantitative or Qualitative?

Completeness requirements are understood quantitatively by the ILCD guideline as the share (%) of a product's actual environmental impact that a study aims to capture. From this understanding, completeness requirements would, for example, be lower for a study that intends to provide an initial screening of hot spots for a company to familiarise itself with the concept of life cycle thinking (e.g. 70%), than for a study that intends to provide an environmental product declaration (EPD) for

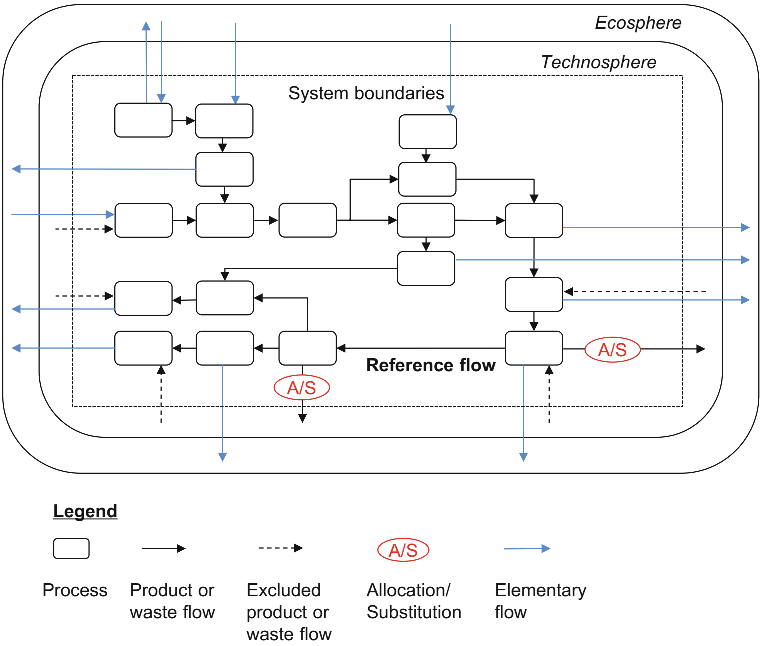

Fig. 8.13 Setting of system boundaries for a realistic product system. In this case, some processes are not included within the system boundaries (cut-off), as illustrated by the excluded product and waste flows. The exact system boundaries depend on whether allocation or substitution is performed in the handling of multifunctional processes

consumers to consider environmental aspects of their purchasing (e.g. 90%). In an LCA guiding the choice between two product designs, the completeness requirement depends on the difference in impact between the product designs. If there is a large (expected) difference, the requirement to completeness would be lower than if the product designs have very similar impacts. In practice, it is often difficult to derive a quantitative completeness requirement from the, generally qualitative, goal definition. In addition, a quantitative completeness requirement is often not helpful for deciding whether a specific process should be included in the system or can be cut-off. To know whether a process can be cut-off one must know how much that process contributes to the total LCIA results for the product system. In other words, one must include the process to figure out if it can be excluded. To circumvent this paradox, some LCA practitioners take a more practical approach by deriving a mass-based cut-off criterion,such as 0.1% from quantitative completeness requirements. This would mean that processes delivering flows with a mass of less than 0.1% of the reference flow can be cut-off. We do not recommend following this approach blindly, because flows that are quantitatively small may still lead to large impacts and therefore have to be included in the modelling. For example, a low mass share of gold in a laptop can account for relatively large impacts due to mining activities, and a small quantity of radioactive waste, e.g. from hospital equipment, can require extensive waste treatment, and therefore be associated with environmental impacts that should not be neglected.

Due to the limitations of working with quantitative completeness requirements, we here advocate a qualitative approach. This means specifying the parts of a life cycle that must be included in the system boundaries and arguing why cutting off other parts is acceptable. For example, an LCA practitioner may know from similar LCA studies or previous experience that transportation between the use stage and the waste management stage, or business trips of the employees of a tier-one supplier are negligible. For new LCA practitioners, it can be difficult to create reasonable completeness requirements and it is therefore always important to explicitly report and justify them. Applying the iterative approach, the omission of any processes should be justified in a sensitivity analysis after the inventory analysis and impact assessment. If the sensitivity analysis indicates that the process may be important with the chosen completeness requirements, it should be included (and perhaps refined) in the next iteration. We stress that an LCA practitioner should not blindly apply "default" qualitative completeness requirements, such as disregarding the production and maintenance of infrastructure, to any study, but always base the requirements on a case-specific assessment. This is to avoid cutting off parts of a life cycle that are important in the specific study, although they may typically not be important.

As with most items of the scope definition, completeness requirements are meant to guide the initial LCI analysis, but during this analysis unforeseen limitations may mean that the requirements are in practice not possible to follow. The LCA practitioner can either handle this situation by modifying the completeness requirements in a new iteration of the scope definition or by explicitly documenting in the LCI analysis the parts of the LCI model that do not fulfil the completeness requirements.

8.7 Representativeness of LCI Data

It is the aim of LCA to reflect physical reality. This means that the model should represent what actually happens or has happened to the extent possible, and the unit processes applied to model the product system must be representative of the processes which are actually used in the analysed product system (in case of attributional LCA) or affected due to the introduction of the assessed product on the market (in the case of consequential LCA).

Typically, parts of a foreground system will be based on data (elementary flows, etc.) collected first-hand by the LCA practitioner, e.g. from the company commissioning the study. This primary data is, provided that it contains no errors, per definition representative of the specific process occurring at the time that the data was collected. Other parts of the foreground system and the entire background system, on the other hand, are constructed from other than first-hand data sources and when doing so it is important to consider how representative the chosen or constructed unit processes are of the actual unit processes that they are models for. Representativeness of LCI data can be understood in three interrelated dimensions: geographical, time-related and technological. Based on the goal definition and knowledge about the studied product system, the scope definition must provide guidance and requirements for the inventory analysis with respect to representativeness of LCI data, as explained below for each dimension of representativeness. Besides serving as a guide for carrying out the inventory analysis, the representativeness of data should also be used in the interpretation of the results to reflect upon the extent to which the product system model corresponds to reality (Chap. 12).

8.7.1 Geographical Representativeness

The geographical representativeness reflects how well the inventory data represents the actual processes regarding location-specific parameters. Geographical representativeness is important to consider because two processes delivering the same product output, but taking place in two different locations (e.g. nations), can be quite different in terms of the other flows (elementary flows, energy flows, material flows and waste to treatment). Differences between unit processes can be caused by geographical differences, such as local climate and proximity to natural resources, and regulatory differences, such as energy taxes and emission thresholds. In addition, when a mix of processes (market mix for attributional LCA and mix of marginal processes for consequential LCA) is used to model the background system or perform system expansion, the location of the mix used in the model versus the actual location of the mix must be considered. For example, the electricity mixes of Denmark (mainly coal and wind power) and Sweden (mainly nuclear and hydropower) vary quite a lot; despite the close proximity of the two countries, see Fig. 8.14.

This can in part be explained by geographical differences (Sweden has mountains and therefore a potential for generating hydropower—Denmark is flat) and in part from social and political differences (Sweden has nuclear power plants—Denmark does not, largely due to public resistance).

Due to the importance of geographical representativeness the LCA practitioner must in the scope definition define the geographical scope of the processes, or combinations of processes, taking place in the product system. The starting point should be the foreground system, where the locations of processes are typically known with high certainty. The LCA practitioner can then proceed to defining the geographical scope of upstream and downstream processes that typically are more uncertain the more "process steps" from the key processes they are in the model. The appropriate resolution of the geographical scopes (e.g. city, region, nation or continent) depends on factors such as the spatial coverage of regulation (typically following national borders), geographical variations (e.g. weather, climate) and the spatial extent of markets (some markets are very local, while others are global).

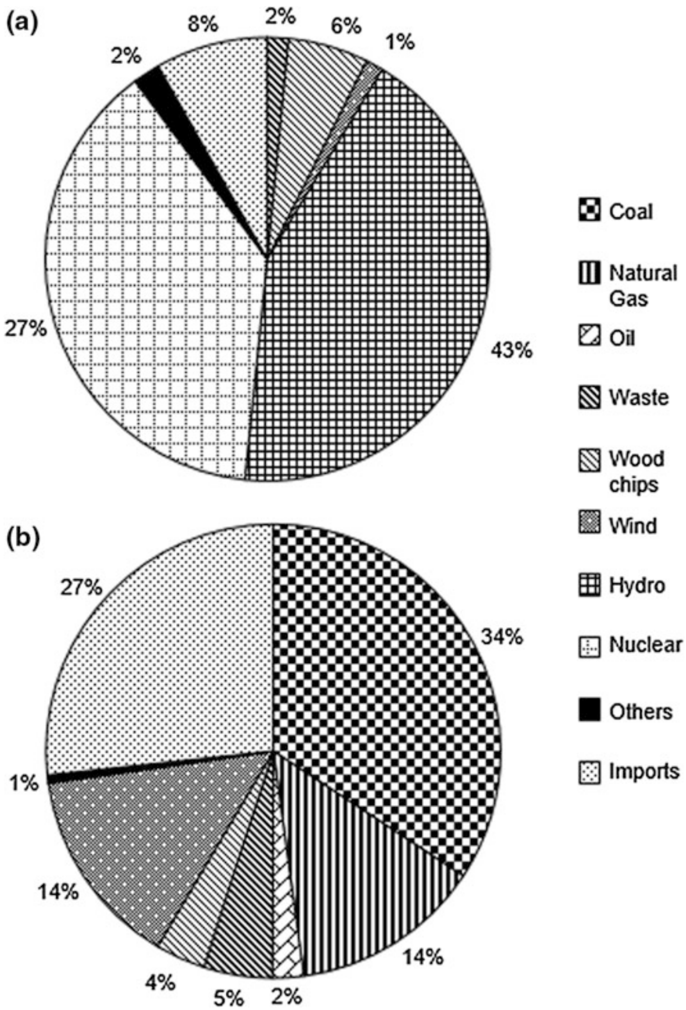

Fig. 8.14 Swedish (**a**) and Danish (**b**) electricity consumption mix in 2014 (low voltage, e.g. for domestic consumption). Imports from neighbouring countries can be further broken down into energy sources. 'Others' is an aggregation of all energy sources contributing less than 1% to the mix (Treyer and Bauer 2013)

Table 8.5 shows the geographical scope for life cycle stages and processes in the illustrative case of window frames (Chap. 39).

During an inventory analysis, it is common that some unit processes cannot be obtained for the described location, such as a specific country. In these cases, the LCA practitioner must choose the most representative unit process to approximate the actual unit process based on his or her knowledge of geographical variations in central factors such as climate, regulation and markets. For example, in a study

Table 8.5 Geographical scope for life cycle stages and central unit processes in the window frames case study

Stage	Window type			
	Wood	Wood/aluminium	PVC	Wood/composite
Materials	Metal ores: not known			
	Crude oil: Norway, Russia, Middle East			
	Forestry: Finland		–	–
Manufacturing	Glass pane: Sweden			
	Wood frame: Scandinavia	Wood frame: Scandinavia	PVC frame: Germany	Composite frame: Germany
	Other elements: Europe	Other elements: mainly Europe	Other elements: mainly Europe	Other elements: mainly Europe
	Assembly: Denmark			
Use (heat supply)	Mainly Scandinavia, Germany	Mainly Scandinavia, Germany	Europe	Mainly Scandinavia
Disposal	The same as the use stage			

involving clothes washing in Vietnam the unit process for a certain waste water treatment process in Thailand may be a good approximation for a Vietnamese unit process if the treatment efficiency is the same, because of the climatic similarities between the two countries. If needed, the proxy process may be adjusted to better represent the actual process of the product system. Chapter 9 elaborates on the choices related to geographical representativeness when constructing an inventory model. The influence of a low geographical representativeness on the conclusionsof the study must be evaluated in the interpretation of the LCA results (see Chap. 12).

8.7.2 Time-Related Representativeness

Just as two processes delivering the same product output can be different if they occur in different locations, they can also be different if they occur at different times. This is due to technological innovation and development, which often tends to lead to more efficient processes over time, meaningless input (energy, material and resource flows) and sometimes also less unwanted by-products (waste to be treated and emissions) per unit of output. The time-related representativeness reflects how well the inventory data represents the actual processes regarding the time (e.g. year) they occur. Technological innovation is "faster" in some sectors than others. Therefore, a unit process that reflects the situation 10 years prior to the occurrence of the process in the product system can have a high time-related representativeness if it belongs to a mature sector with little technological

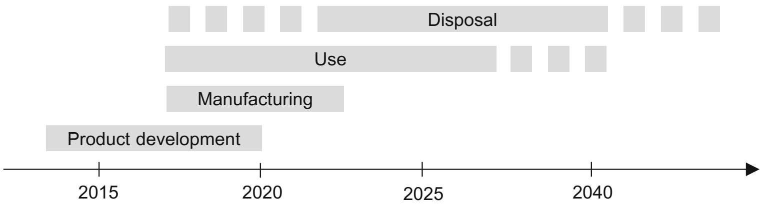

Fig. 8.15 Example of time frames expressed for different life cycle stages

innovation (such as the pulp and paper industry); but it can have a low representativeness if it is part of a sector with rapid technological development, such as IT, energy (with the growing focus on decarbonisation) and waste treatment (with the focus on waste avoidance and recycling of materials).

In line with the requirements to define the geographical scope of processes, LCA practitioners must in the scope definition define the time frame of the processes in the different stages of the life cycle. Figure 8.15 gives an example of how time frames can be represented.

These times are largely influenced by the expected lifetime of the studied product(s). For example, in a study involving furniture the expected lifetime, from consumer purchase to disposal, is decisive for the time at which waste treatment can be expected to occur. In other cases, the lifetime of installed capacity in the foreground system has a great influence on the time frames. For example, in a study involving a decision to construct a new incineration plant, the number of years that it is planned to operate (typically 20–30 years) is decisive for the timing of the involved unit processes. In all cases, the intended application of results and reasons for carrying out a study, as stated in the goal definition, can guide the time-related requirements. In the illustrative case study on window frames, the time frame of the manufacturing and use stage is estimated to be 5 and 20 years, respectively.

Following the formulation of the time-related requirements, the LCA practitioner must attempt to obtain the highest overall possible time-related representativeness when constructing the inventory model, within the time or budget constraints of the LCA study. When comparing the time aspects of the obtained inventory data with the time-related requirements it must be noted that the time at which a dataset was published is usually not equivalent to the time for which its data is valid (several years may pass between the first-hand collection of data and the publication of the data). In the foreground system the focus should be on those processes taking place in the future that the results of an initial iteration show to be important and that is also expected to change relatively rapidly (see above). The available current or past data for these processes can be used to project how they will evolve in the future. For example, the electricity mix of the future might be projected from past trends along with plans issued by public authorities that govern the electricity system. See also Chap. 21 on prospective LCAs and technological foresight. Regarding the background system, LCA practitioners usually have to make do with the most recent process contained in the LCI database used, while considering any trade-offs with geographical representativeness. The influence of a low time-related representativeness on the conclusions of the study must be evaluated in the interpretation of the LCA results (see Chap. 12).

In comparative studies it is important to investigate whether there is a risk that differences in time-related representativeness for the compared alternatives can lead to a bias that favours one product system over the others. This could, for example, be the case in a comparison of two technologies if the data of one technology is older (in terms of the year they are valid for) than the data of the other technology.

Just as some LCIA methods are spatially differentiated, there are also LCIA methods that are temporarily differentiated, meaning that their results are affected by the timing of elementary flows (see Chap. 10). So far, this LCIA practice has been limited to mainly distinguishing between "short-term" and "long-term" emissions, which is, for example, relevant when including landfilling processes, from which some emissions are projected to occur hundreds or even thousands of years after the landfilling of a given material. In addition, some climate change indicators consider when an emission occurs, which, for example, enables quantification of the benefits of temporary carbon storage. In specific cases, the difference of inventory data in the course of the year (especially hot and cold season) and the day (daytime/night) are relevant for a study. It is to be checked along the goal of the study whether such intra-annual or intra-day specific data might be needed (e.g. on night-time electricity base-load data for charging electric car batteries overnight). In all cases, the time-related information for elementary flows required by the LCIA methods chosen in the previous step of the scope definition should guide the data collection and output format of the inventory analysis.

8.7.3 Technological Representativeness

Two identical products can be produced using two different technologies and thereby be associated with different (sets of) unit processes and related flows. For example, crude steel can be produced using an electric arc furnace (EAF) or a basic oxygen furnace (BOF), which are two very different technologies involving different inventory flows. Technological representativeness reflects how well the inventory data represents the actual technologies involved in the studied product system. Technological representativeness is interlinked with geographical and temporal representativeness. For example, the technology mix involved in the production of electricity (coal power, natural gas, nuclear power, windmills, etc.) varies in space (e.g. from country to country) and over time. The LCA practitioner must use his or her knowledge about the product system to ensure (to the highest degree possible) that it is modelled using unit processes that reflect the actual technologies involved. It is important to ensure that the unit processes modelled in the system are in fact internally technologically compatible, meaning that the product output of one process should meet the quality requirements for input materials of the next process in the system. For example, if a unit process requires steel that is stainless and heat resistant as material input, then it is incompatible with the product of a unit process producing basic grade steel without these properties.

The scope definition should therefore contain a list of technologies that are known to be involved in the foreground system and in those parts of the background system for which such knowledge exists (typically energysupply, waste management and transportation), specifying representativeness requirements. This list should be partly based on the outcome of the geographical scope and time frames in terms of where and when processes are taking place.

8.8 Preparing the Basis for the Impact Assessment

The planning of the impact assessment in the scope definition has two main purposes. The first is to ensure that it is done in accordance with the goal definition and the second is to prepare for the inventory analysis where the elementary flows (resources and emissions) that should be included depend on the impact categories to be covered in the LCIA. These elementary flows may also depend on the particular LCIA methods that are used to model these impact categories because different LCIA methods can cover different elementary flows. Planning how to perform the LCIA prior to the life cycle inventory analysis therefore helps ensuring that the right data is being collected in the cycle inventory analysis. A brief guidance on the planning of the LCIA is given in the following sections. Chapter 10 gives a comprehensive introduction to the science behind LCIA and how to report results.

8.8.1 Selection of Impact Coverage

According to the ISO 14044 standard for LCA, the selection of impact categories to be covered by an LCA "shall reflect a comprehensive set of environmental issues related to the product system being studied, taking the goal and scope into consideration". This means that all environmental impacts where the product system has relevant contributions must be included in the impact assessment, unless the goal definition explicitly states otherwise. The latter is the case, e.g. in carbon or water footprinting studies, and in such studies the limitations imposed by the narrow impact coverage should be stressed in the goal definition and addressed the interpretation of results. Other valid reasons to exclude one or more impact categories from the assessment is when an initial iteration of the LCA shows that they do not contribute to the differentiation between the alternatives in a comparative LCA, or when they have a negligible contribution to the overall impacts, estimated by aggregating indicator scores for different impact categories to a single score following normalisation and weighting (see Sect. 8.2.5). In this case, the excluded impact categories must be listed as deliberately omitted in the scope definition of the LCA report with reference to the outcome of the initial iteration. Transparency on the selection of impact categories is essential to avoid an "interest-driven" selection of impact categories where impact categories are excluded, e.g. because they disfavour the product produced by the commissioner of a study in a comparative analysis.

8.8.2 Selection of LCIA Methods

To support the choice between alternative LCIA methods that can be used to calculate an indicator score for the same impact category, ILCD has developed six criteria for evaluating the methods:

1. Completeness of scope: how well does the indicator and the characterisation model cover the environmental mechanisms associated with the impact category under assessment?
2. Environmental relevance: to what extent are the critical parts of the impact pathway included and modelled in accordance with the current state of the art?
3. Scientific robustness and Certainty: how well has the model been peer reviewed, does it represent state of the art, can it be validated against monitoring data and are uncertainties reported?
4. Documentation, Transparency and Reproducibility: how accessible are the model, the model documentation, the characterisation factors and the applied input data?
5. Applicability: are characterisation factors provided for the important elementary flows for this impact category in a form that is straightforward to apply?
6. Stakeholders' acceptance: has the model been endorsed by competent authorities, are the model principles and applied metric understandable for users of the LCA results in a business and policy contexts?

These criteria can be difficult to apply for LCA practitioners that are not experts in LCIA modelling, but further insight can be gathered in Chaps. 10 and 40 gives an overview of available LCIA methods, discusses their main differences and how they perform on the six criteria.

In practice, an LCA practitioner will often rely on the use of software to model the product system and perform the impact assessment and then simply calculate LCIA scores for all the impacts categories that are made available in the software as part of an LCIA method. An LCIA method is a collection of impact categories that aims to have a broad coverage of environmental issues, and it is typically developed by one research group (Hauschild et al., 2013). If several LCIA methods are available, it may be useful to apply more than one to test the sensitivity of the results to the choice of LCIA method (see Chap. 11). This is an easy way to explore the sensitivity of LCIA results because calculating results for multiple impact categories in LCA software essentially takes the same time as calculating results for a single impact category.

For some LCA studies, no LCIA method may cover an environmental impact that is considered relevant. In such cases, the LCA practitioner can choose to develop an LCIA method on their own and this development should be guided by the six criteria above. Often, however, the development of a new impact category is not feasible for an LCA practitioner, due to budget constraints and limited knowledge of the impact pathway. The potentially relevant environmental impacts that are not covered by the impact assessment should be highlighted in the scope definition and considered qualitatively in the interpretation of results (Chap. 12).

An important aspect related to compatibility between the collected elementary flow of the life cycle inventory analysis and the ensuing LCIA is the degree of spatial differentiation of the LCA study. Spatial differentiation essentially means taking into account where an elementary flow occurs. This information is relevant for many impact categories, because the sensitivity of the environment towards 1 unit of elementary flow differs from place to place (see more details in Chap. 10). Many popular LCIA methods are (still) spatially generic. Yet, spatially differentiated methods have over the years increased in numbers and quality and their use may therefore increase in the future. If it is chosen to use spatially differentiated methods it is important to collect spatial information for the elementary flows in the life cycle inventory analysis (e.g. name of nation, watershed ID or grid cell defined by GIS coordinates) that is compatible with these methods.

Normalisation and weighting are optional LCIA steps under ISO 14044:2006, and as part of the scope definition the LCA practitioner should decide whether normalisation and weighting is needed. Are the steps relevant for the intended application(s) and target audience of the LCA study (see Goal definition in Chap. 7)? Normalisation is usually beneficial to aid the understanding of results if the target audience are not experts, and weighting is required if an aggregation of impact scores across the environmental impact categories is intended. On top of normalisation, an LCA practitioner may thus choose to include weighting, if the commissioner of a study has specifically asked for single score results. The decision to perform normalisation and weighting can also influence the choice of LCIA method since not all methods support these steps. A detailed description of normalisation and weighting is given in Chap. 10.

8.9 Special Requirements for System Comparisons

Many LCA studies compare systems, e.g. when two or more products fulfil the same function as captured in the functional unit. The ISO 14044 standard poses a number of special requirements for the scope definition of comparative studies to ensure that the systems can actually be compared: “Systems shall be compared using the same functional unit and equivalent methodological considerations, such as performance, system boundary, data quality, allocation procedures, decision rules on evaluating inputs, and outputs and impact assessment. Any differences between systems regarding these parameters shall be identified and reported". When a comparative study is intended to conclude on the superiority or equivalence of the compared alternatives in terms of their environmental performance, and to make these conclusions publically available, the standard identifies it as a "comparative assertion intended to be disclosed to the public". For such applications of LCA, the standard requires that these points shall be evaluated in a critical review performed by a panel of interested parties (see Sect. 8.10 and Chap. 13).

These special requirements reflect the consequences that the comparative use of LCA results may have for other companies, institutions and stakeholders that are not directly involved in the study and they are intended to prevent the misuse of LCA in market competition.

To prevent misleading LCA results and the misuse of LCA in comparative assertions, the ILCD guideline furthermore requires that:

- The uncertainties involved must be evaluated and communicated when one product system appears to have a lower environmental impact for one or more impact categories than another, see Chaps. 11 and 12 for details.
- In the case where the goal definition prescribes a comparison based on a single indicator (e.g. carbon footprint) the LCA study must highlight that the comparison is not suitable to identify environmental preferable alternatives, as it only covers the considered impact(s) (e.g. climate change). This applies unless it can be sufficiently demonstrated that the compared alternatives do not differ in other relevant environmental impacts to a degree that would change the conclusions of the comparison if those other impacts would be included in the analysis. Such demonstrations may be in the form of other LCA studies available for sufficiently similar systems.

8.10 Need for Critical Review

A critical review is performed by experts not involved in making a study. A critical review is sometimes required (e.g. for studies with the intended publication of results), but even when there is no formal requirement a critical review is useful for improving the quality and credibility of a study.

Chapter 13 deals specifically with the critical review stage of an LCA, presents the different types of critical review and explains for what kind of LCA studies (with reference to the goal definition) these are needed. It is, however, useful already during the scope definition to decide whether a critical review is needed or intended. If a review is required or intended, the scope definition should furthermore specify the form of the review in order to allow the documentation and reporting of the study to be tailored to meet the later requirements from the peer reviewers. It should also, in the scope definition, be decided whether the review should be performed on the final draft of the LCA report or whether it should be done in an interactive process throughout the performance of a study. In this case, the reviewers are given the opportunity to comment on the goal and scope definition prior to the onset of the inventory analysis, and possibly on interim results of the impact assessment and interpretation before the final reporting so that their comments can guide the process of the LCA.

8.11 Planning the Reporting of Results

Product systems can be very complex, and choices are often made during the LCA that can influence the conclusions. To reduce the risk of erroneous and misleading use of the LCA, it is essential that the reporting is clear and transparent with a clear indication of what has and what has not been included in the study and which conclusions and recommendations the outcome supports.

The reporting of an LCA study should target the audience as it is specified in the goal definition. Depending on whether the study is comparative and public, the ILCD guideline identifies three reporting levels:

1. Internal use by the commissioner of study;
2. External use by the third party, i.e. a limited, well-defined list of recipients with at least one organisation that has not participated in the study.
3. Comparative studies to be disclosed to the public.

Due to the sensitive nature of comparative assertions based on LCA, there are a number of additional reporting requirements to level 3 studies. No formal requirements apply to level 1, but it is recommended to follow the requirements for level 2. Chapter 38 shows all the elements that an LCA report should cover, according to level 2 and 3, and proposes a sequence of these elements, and the reporting of the case study on window frames in Chap. 39 demonstrates the application of the template in a comparative study.

References

This chapter is to a large extent based on the ILCD handbook and the ISO standards 14040 and 14044. Due to the scope of this chapter, some details have been omitted, and some procedures have been rephrased 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. First edition March 2010. EUR 24708 EN. Publications Office of the European Union, Luxembourg (2010)

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