LCA Compendium – The Complete World of Life Cycle Assessment
Series Editors: Walter Klöpffer · Mary Ann Curran

Andreas Ciroth
Rickard Arvidsson *Editors*

Life Cycle Inventory Analysis

Methods and Data

Springer

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Series Editors
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Aims and Scope

Life cycle assessment (LCA) has become the recognized instrument to assess the ecological burdens and human health impacts connected with the complete life cycle (creation, use, end-of-life) of products, processes, and activities, enabling the assessor to model the entire system from which products are derived or in which processes and activities operate. Due to the steady, world-wide growth of the field of LCA, the wealth of information produced in journals, reports, books, and electronic media has made it difficult for readers to stay abreast of activities and recent developments in the field. This led to the realization of the need for a comprehensive and authoritative publication.

LCA Compendium – The Complete World of Life Cycle Assessment discusses the main drivers in LCA (SETAC, ISO, UNEP/SETAC Life Cycle), the strengths and limitations of LCA, the LCA phases as defined by ISO standards, specific applications of LCA, Life Cycle Management (LCM) and Life Cycle Sustainability Assessment (LCSA). Further volumes, which are closely related to these themes will cover examples of exemplary LCA studies ordered according to the importance of the fields of application. They will also present new insights and new developments and will keep the whole work current. The aim of the series is to provide a well-structured treatise of the field of LCA to give orientation and guidance through detailed descriptions on all steps necessary to conduct an LCA study according to the state of the art.

LCA Compendium – The Complete World of Life Cycle Assessment anticipates publishing volumes on the following themes:

- Background and Future Prospects in Life Cycle Assessment (published in March 2014)
- Goal and Scope Definition in Life Cycle Assessment (published in September 2016)
- Life Cycle Inventory Analysis (LCI) – Methods and Data (published 2021)
- Life Cycle Impact Assessment (LCIA) (published in March 2015)
- Interpretation as well as, Critical Review and Reporting in Life Cycle Assessment (in print 2021)
- Special Types of Life Cycle Assessment (published in July 2016)
- Life Cycle Management (LCM) (published in August 2015)
- Life Cycle Sustainability Assessment (LCSA)
- Life Cycle Assessment Worldwide

More information about this series at http://www.springer.com/series/11776

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ISSN 2214-3505 ISSN 2214-3513 (electronic)
LCA Compendium – The Complete World of Life Cycle Assessment
ISBN 978-3-030-62269-5 ISBN 978-3-030-62270-1 (eBook)
https://doi.org/10.1007/978-3-030-62270-1

This Springer imprint is published by Springer Nature The registered company is Springer Science+Business Media B.V. Dordrecht.
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

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Not just since the Fridays for Future movement, which began August 2018, but since decades, foresighted public policy making, corporate supply chain management and product development rely on an environmental life cycle perspective. Governments, administrations, and companies use the results of environmental life cycle assessments of packaging materials, fuels based on renewable materials, or of their full supply chains to identify hotspots, improvement potentials, and new regulatory measures.

Two elements of the life cycle inventory (LCI) analysis are key for the reliability and quality of the outcomes of an LCA (life cycle assessment): the system model and the life cycle inventory data. Similar to a civil engineer, who uses a simplified model to dimension the load-bearing structure of a building, the LCA practitioner designs a simplified system model to represent the product system under analysis that is suited for the goal for which the LCA is carried out. Rosenblueth and Wiener (1945) claimed in their paper on the role of models in science that "the best material model for a cat is another, or preferably the same cat." This is not practical but tempting. Increasing both the geographic and time resolution of LCIs, for instance, is a challenge for the model design. The art of parsimonious model design which helps to address the most pressing environmental issues and eliminate the main causing industrial or agricultural activities is to capture the characteristics of the object of investigations and its supply chains, which are relevant in relation to the goal and scope of the LCA. This is where brainpower should replace simplified mechanistic models on one hand and time and computing power needed to establish overly complex system models, and to calculate the environmental footprints of products, services and organizations on the other.

*Rolf Frischknecht, jointly with Reinout Heijungs, has been the founder of the volume "Life Cycle Inventory Analysis". He created the nucleus and developed the fundamentals of the concept. Finally, he delegated his responsibility as editor to Andreas Ciroth and Rickard Arvidsson who further developed the concept and brought the volume to finalization. See also chapter 4 of this volume "Multi-functionality in Life Cycle Inventory Analysis: Approaches and Solutions" by Jeroen Guinée, Reinout Heijungs and Rolf Frischknecht.

Once the appropriate system model is ready, appropriate LCI data is needed. While LCI data was hardly publicly available in the infancy of LCA (1970–1990), the first material, comprehensive, consistent, topical, transparent, and quality controlled LCI databases were established, further developed, and expanded in the last 30 years (Frischknecht et al. 1994, 2004). The LCI datasets offered in these databases address those human activities that are causing a large share of societies' impact on the environment (materiality). They cover a broad set of elementary flows and include capital goods (comprehensiveness); follow a strict set of modeling guidelines, including allocation and electricity mix modeling (consistency); use most recent information as far as possible, feasible, and available (timeliness); are reported on a unit process gate to gate level which allows for a duplication of the LCI results (transparency, see also Frischknecht 2004); and are reviewed by an external independent third party (quality control). In addition, LCI data must represent real situations, and the documentation in a dataset must refer to its LCI data (reality check). Third parties should be able to crosscheck the references used to establish a certain amount of input or a certain emission factor reported in the dataset. Despite all these characteristics and requirements, the LCI datasets offered remained fairly simple and clear.

In all those years since the dawn of unified LCI databases, the following controversial discussions were loyal companions of LCI database operators and LCA practitioners:

a) Allocation and recycling: credits or no credits – that is the question. Credits are tempting, but they challenge inter-generational equity and fair environmental competition.
b) Attributional or consequential: it is a dream to quantify the environmental impacts caused by decisions. However, it is very difficult, if not impossible, to establish stringent causal relationships between an individual decision and the impacts it causes, unless the decision is about a really big thing. While simple and mechanistic rules were used in the past (Ekvall and Weidema 2004), consequential LCAs nowadays make use of general and partial equilibrium models and plug in traditional LCAs (e.g., Igos et al. 2015).
c) Process-based or input-output based LCA: while precision versus completeness dominated the debate on the more appropriate approach in the past, the two approaches are subsequently used to quantify the supply chain of environmental impacts of organizations. Input-output based assessments are carried out, firstly, to identify potential hotspots within the supply chains of organizations. Secondly, process based LCA is then used to identify improvement potential within the hotspot areas.

The task of LCI experts and LCI database providers resembles the work of a ferryman: it is a service to life cycle practitioners, with recurring tasks of regularly updating LCI data of the same or similar commodities and with recurring methodological discussions. In that sense, this type of work has a meditative character. At the same time, this work is of utmost importance because LCI databases are the core foundation of many, if not all, LCAs and their conclusions and recommendations. A solid LCI foundation is a necessary but not a sufficient prerequisite for solid LCAs with solid recommendations in view of a society that strives to live within the boundaries of our planet Earth.

This book *Life Cycle Inventory Analysis – Methods and Data* is a milestone in the history of LCI methodology and analysis and of LCA in general. It gives an excellent overview on the current state of discussions and technical developments and possibilities. I am convinced that it will help to generate and maintain robust and appropriate LCI data and models suited to address the multiple pressing environmental challenges we face.

November 2019

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Chapter 1
Introduction to "Life Cycle Inventory Analysis"

Rickard Arvidsson and Andreas Ciroth

Abstract This chapter introduces the life cycle inventory (LCI) analysis – the topic of this volume. A brief history of the concept is provided, including its procedure according to different standards and guidance books. The LCI analysis phase of the life cycle assessment (LCA) framework has remained relatively constant over the years in terms of role and procedural steps. Currently, the LCI analysis is situated in between the goal and scope definition phase and the life cycle impact assessment phase in the LCA framework, although it is interconnected also with the interpretation phase. Central concepts in LCI analysis are defined, including product system, process, flow, functional unit, and system boundary. Four important steps of LCI analysis are outlined: constructing a flow chart, gathering data, conducting calculations, as well as interpreting results and drawing conclusions. The focus is on the process LCA approach, which is the most common in LCA practice. Environmentally-extended input-output analysis is also described briefly. Finally, an overview of the other chapters of this volume and their relevance to the topic of LCI analysis is provided.

Keywords Allocation · Data gathering · Environmentally-extended input-output analysis · Inventory · Life cycle assessment (LCA) · Life cycle impact assessment · Life cycle inventory analysis (LCI)

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A. Ciroth, R. Arvidsson (eds.), *Life Cycle Inventory Analysis*, LCA Compendium – The Complete World of Life Cycle Assessment,
https://doi.org/10.1007/978-3-030-62270-1_1

1 A Brief History of Life Cycle Inventory Analysis

An important role of life cycle assessment (LCA) is to contribute to sustainable product development. In order to do so effectively by assessing negative environmental consequences and trade-offs with other sustainability aspects, an LCA study needs "to be as quantitative as possible" (Klöpffer 2003). Since the first attempts to formalize the life cycle assessment (LCA) framework, life cycle inventory (LCI) analysis has been a central part. No wonder, because in order to conduct a quantitative environmental assessment, obtaining quantitative data related to the object of study is crucial, and this is a core step of LCI analysis. In fact, the LCI analysis might be older than the LCA framework itself, of which it is currently seen as a part, considering early accounts of life cycle energy requirements at an inventory level in the 1970s (Hannon 1972; Makhijani and Lichtenberg 1972). Despite its long history, the definition and procedure of the LCI analysis has remained relatively constant over time, although some details vary between different sources.

In the early work on LCA (1970–1990), the LCI analysis was sometimes considered to contain the definition of goal and scope (Vigon et al. 1993). One of the earliest attempts to harmonize the LCA framework was conducted in the Code of Practice by the Society of Environmental Toxicology and Chemistry (SETAC) (Consoli et al. 1993). In this work (and onwards), the LCI analysis phase is seen to be separate from the goal and scope definition (Fig 1.1a). The steps included in the LCI analysis according to the Code of Practice are: (1) defining systems and system boundaries; (2) creating process flow charts; (3) gathering, calculating, and reporting data; and (4) conducting allocation (if coproducts or recycling processes exist in the system). It is further described that all inputs and outputs for which data has been found should be scaled to the functional unit of the study, which is still common practice in LCA today.

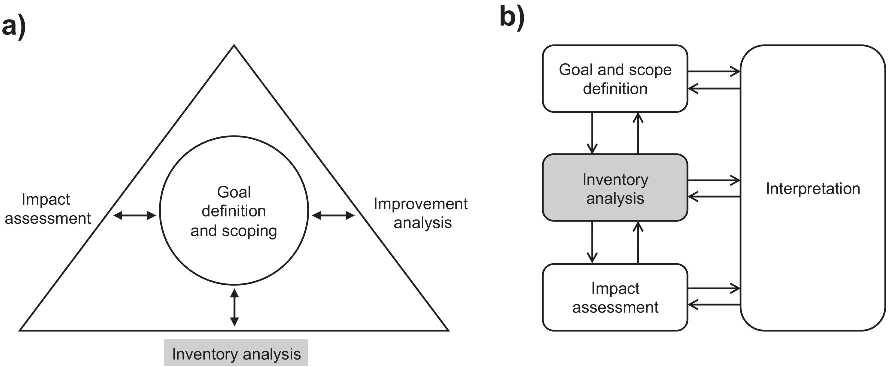

Fig. 1.1 Life cycle assessment frameworks from SETAC's Code of Practice (Consoli et al. 1993) (**a**) and from the most recent ISO standard (2006) (**b**), with the life cycle inventory analysis phase highlighted in gray in both cases

The Nordic Guidelines on LCA from 1995 state that the LCI analysis contains the following steps, where, in particular, (1) and (2) are similar to (1) and (3) in SETAC’s Code of Practice, respectively: (1) Description of the product system (functions and boundaries), (2) data collection and calculations, as well as (3) a sensitivity and uncertainty assessment (Lindfors et al. 1995). In an early handbook on LCA, Boguski et al. (1996) outline five steps of LCI analysis: (1) define the scope and boundaries, (2) gather data, (3) create a computer model of the product system studied, (4) analyze and report the study results, and (5) interpret the results and draw conclusions. The first two steps are similar to those in the Nordic Guidelines. An 8 years newer textbook provides a different set of three steps for conducting an LCI analysis, where step (2) about data gathering is common between the two books: (1) construction of the flow chart, (2) data collection, and (3) calculation of emissions and resource use (Baumann and Tillman 2004). Although SETAC’s Code of Practice, the Nordic Guidelines and the two books use somewhat different wording, they convey a similar procedure in practice and several of the steps are shared almost literary between these guidance texts.

The most recent 2006 ISO standard for LCA, as well as the previous ISO standard from 1997, provide the currently widely accepted framework for LCA, with the LCI analysis placed in between the goal and scope definition and the life cycle impact assessment (LCIA) phases (Fig 1.1b). The 2006 standard states that the LCI analysis phase includes “data collection and calculation procedures to quantify relevant inputs and outputs of a product system.” It specifically lists three important steps of an LCI analysis: (1) data collection, (2) data calculation, and (3) allocation of flows and releases, where the last step can be seen as a specific type of calculation. These three steps can be recognized in several of the previously cited sources, such as SETAC’s Code of Practice (all three), the Nordic guidelines (the first and second), and the textbook by Baumann and Tillman (2004) (the first and second).

As all phases in the current LCA framework, the LCI analysis is iterative and connected to the other phases (ISO 2006). Typically, the LCA analyst learns more about the system under study during the LCI analysis, which can sometimes have implications for the other phases. For example, if data is found to be exceptionally scarce during the data gathering of the LCI analysis, the goal and scope of the study might have to be redefined. The analyst might then need to lower the ambition of the study in different ways, for example, by reducing the number of included impact categories. The other phases of the LCA framework might also warrant a revisiting of the LCI analysis. For example, if the LCIA phase shows strange or even unreasonable impact results, the LCI analysis might have to be revisited to improve the data coverage and/or quality. The LCI analysis is thus an integrated part of the LCA framework and procedure rather than an isolated step to be ticked off.

2 LCI Analysis in a Nutshell

The ultimate purpose of the LCI analysis is generally to use the inventory data result in the subsequent LCIA step for calculating environmental impacts by using the following equation (Hauschild and Huijbregts 2015):

$$IS_j = \sum_i \sum_k \sum_l Q_{i,k,l} CF_{j,i,k,l} \tag{1.1}$$

where *IS* stands for impact score (e.g., climate change), CF stands for characterization factor, *Q* stands for the quantity of emission or resource use from the inventory, *i* is a certain contributor (emission or resource) to the impact category *j*, *k* is the location of the emission or resource use, and *l* is the environmental compartment to which the emission occurs or from which the resource is extracted.

Before describing how to conduct an LCI analysis to obtain emission and resource use quantities *Q*, a number of important concepts need to be defined. These entities are shown in italic below and their definitions are modified from those in the ISO standard (2006). The very object of study in an LCI analysis is the *product system*, which is a set of processes that are connected by energy and/or material flows. In addition, the product system must perform one or more of the functions outlined in the goal and scope definition phase. *Processes*, in turn, are nodes in the societal metabolism where flows meet and can be transformed. A *unit process*, specifically, is the least aggregated process level in the product system. Unit processes are thus the building blocks of a product system, much like brick stones are building blocks of walls. The above-mentioned *flows* are movement of energy and/or materials, which can be of different types. *Outputs* are flows that leave a process, whereas *inputs* are flows that enter a process. Examples of outputs are emissions to the environment (air, water, or soil), by-products, waste, and flows that enter other processes for further handling. Inputs can be resources from the environment or flows from upstream processes in the product system. *Elementary flow* is a specific term for flows leaving or entering the natural environment. The *functional unit* is the quantified performance of the product system, which is the reference unit to which all flows are scaled in the LCI analysis phase. The *system boundary* is the border between a product system, the natural environment, and other product systems. The system boundary thus delimits the product system to be studied.

In this section, we describe four steps that can be found in guidance documents on LCI analysis (Sect. 1). The first three specifically correspond to those in the textbook by Baumann and Tillman (2004): (1) constructing a flow chart, (2) gathering data, and (3) conducting LCI calculations. In addition, we follow the early handbook by Boguski et al. (1996) and include a fourth step: (4) interpreting results and drawing conclusions.

2.1 Constructing a Flow Chart

A step frequently mentioned in guidance documents on LCI analysis is the construction of a flow chart (Sect. 1). Two simple examples of flow charts are provided in Fig. 1.2. Flow charts depict the processes included in the product system, usually represented by boxes, as well as material and energy flows within the product system, usually represented by arrows. When constructing a flow chart, the analyst typically departs from the product or main (foreground) system studied. The inputs to that system are then identified. Then, the processes from which they originate are identified. For these processes, their inputs are then identified, and so on. The graphical illustration of the result of this procedure is the flow chart. Heijungs (2014) provided the following five useful recommendations for drawing a flow chart:

- Processes are represented by boxes
- Products (including services and waste) are represented by arrows between boxes
- The main direction must be chosen, e.g., from top to bottom or from left to right, although some loops may be present
- Environmental interventions are not shown because the diagram focuses on the structure of the processes
- Numbers are not shown (for the same reason)

Note that we do not follow the fifth recommendation in Fig. 1.2 – numbers are displayed there to facilitate an example calculation later in this section. In real-world LCA studies, such data can indeed preferably be provided outside the flow chart.

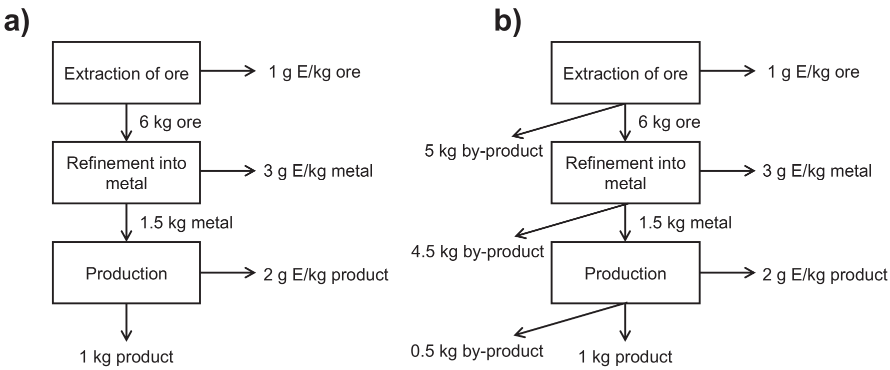

Fig. 1.2 Illustration of two flow charts that can be used to calculate life cycle inventory data results, one without by-products (**a**) and one with by-products (**b**)

2.2 Gathering Data

The LCI analysis is about creating the LCA model, and an evidently crucial part of setting up the model is data gathering. As shown in Sect. 1, this is a core step in most guidance documents on LCI analysis. Specifically, data gathering regards the collection of data for the parameter Q in Eq. 1.1, or for parameters from which Q can be estimated. Inventory data need to be gathered for all the unit processes of the product system (ISO 2006). The LCI analysis is often said to be the most time-consuming and labor-intensive phase of an LCA. For any LCA with more than a few processes readily available in LCI databases, this is probably true.

The exact procedure of data gathering is highly dependent on the type of LCA study as specified in the goal and scope definition, and may therefore vary between LCA studies. Already Consoli et al. (1993) listed a number of potential data sources, including:

- Process designers
- Engineering calculations
- Estimations from similar operations
- Commercial databases

Although formulated almost 30 years ago, these data sources broadly reflect the current LCA practice. Often, a product system is divided into a foreground system of processes central to the studied product (that a certain actor can influence) and a background system of inputs purchased from global markets (that is beyond the influence of a certain actor), a division proposed by Tillman (2000). Additional important sources of data, in particular, for the more in-depth studied foreground system of an LCA, include scientific papers, governmental and industry reports, environmental statistics, as well as various expert judgments. Today, LCA databases provide generic data suitable for the background systems of most studies, see also Chap. 6.

2.3 Conducting LCI Calculations

Regarding the calculations of the LCI analysis, Suh and Huppes (2005) describe that the most common approach is through flow charts. This approach is referred to as process or process-based LCI analysis (Nielsen and Weidema 2001; Rebitzer et al. 2002). By departing from the functional unit of the study, flows are traced backward and forward until they cross the system boundary of the flow chart, at which point the amount of input or output is recorded. The more complicated the product system is, the less simple the calculations become. Complicating factors include processes that produce several output flows or receive several input flows, as well as loops within the system. To illustrate the varying difficulty of conducting an LCI analysis given differently complicated flow charts, Fig. 1.2 shows two

Table 1.1 Example of a simplified unit process for the production process in Fig. 1.2b

Flow	Quantity	Unit
Input		
Metal	0.5	kg/kg product
Output		
Product	1	kg/kg product
By-product	0.5	kg/kg product
Emission E	2	g/kg product

examples, where the data presented can be seen as the result of data gathering activities as described in Sect. 2.2. To make the illustration easy to understand, the two examples include only one generic emission E (corresponding to Q in Eq. 1.1) as output apart from the main product and by-products. The flow charts in Fig. 1.2 show simple, cradle-to-gate product systems. They consist of three unit processes each: extraction of ore, refinement into metal, and production of the product. The data for each of these processes can be expressed as a unit process – Table 1.1 shows a simplified unit process for the production process in Fig. 1.2b. Such unit processes are the building blocks of the process LCI analysis.

Inventory results for emission E (m_{E}) can then easily be calculated as for the system in Fig. 1.2a:

$$m_E = 2 + 1.5 \times 3 + 6 \times 1 = 12.5\,\mathrm{gE/kg\ \ product} \tag{1.2}$$

An alternative way to calculate inventory results is using the matrix approach, where the LCI inventory result is a matrix (vector) **M** with the different emissions and resources used in the rows (Suh and Huppes 2005). To calculate **M**, one then needs to define a technology matrix **A** with unit-process input commodities (e.g., crude oil and metal ore) in its rows and processes (e.g., production and use) in its columns. If a commodity is an output to a process, it is given a positive sign (+), and conversely, if a commodity is an input, it is given a negative sign (−). In addition, the matrix **B** is defined to be a matrix containing the emissions and resource use for each process, thus with emissions and resources in its rows and processes on its columns. Finally, **k** is defined as a matrix (vector) containing only the functional unit of the study. The LCI result of the system in Fig. 1.2a can be calculated using the matrix approach as follows, giving the same result as Eq. 1.2:

$$\begin{aligned} \mathrm{M} = \mathrm{BA}^{-1}\mathrm{k} &= \begin{bmatrix}1 & 3 & 2\end{bmatrix}\begin{bmatrix}1 & -4 & 0\\ 0 & 1 & -1.5\\ 0 & 0 & 1\end{bmatrix}^{-1}\begin{bmatrix}0\\0\\1\end{bmatrix} = \begin{bmatrix}1 & 3 & 2\end{bmatrix}\begin{bmatrix}1 & 4 & 6\\ 0 & 1 & 1.5\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}0\\0\\1\end{bmatrix} \\ &= \begin{bmatrix}1 & 7 & 12.5\end{bmatrix}\begin{bmatrix}0\\0\\1\end{bmatrix} = 12.5\,\mathrm{gE/kg\ \ product} \end{aligned} \tag{1.3}$$

Since only one generic emission E is considered, the **B** matrix becomes a vector in this example. For more than one type of emission and/or resource use, it would become a nonvector matrix.

One complicating factor mentioned above is the case of several outputs, which can be referred to as the multifunctionality problem in LCA (Guinée et al. 2004). In Fig. 1.2b, the challenge of several output flows is introduced by adding a by-product for each of the processes. Multifunctionality can be handled in different ways. The ISO standard (2006) for LCA mentions three options in order of preference:

1. Avoid allocation by dividing multifunctional processes into subprocesses or expanding the system to include additional functions related to the coproduct
2. Partition between different products based on physical relationships
3. Partition between different products based on other relationships, such as economic value

In addition to these three options proposed by the ISO standard, additional allocation approaches are possible (Majeau-Bettez et al. 2018). The first option mentioned in the standard is often executed through expanding the system to include the use of the by-products and the substitution (disuse) of some other product fulfilling the same function, as described by Weidema (2000). The inventory data of the substituted products are then subtracted from that of the main product. Regarding partitioning based on physical properties, a common example is to partition based on the mass of products:

$$P_{i,mass} = \frac{n_i m_i}{\sum_i n_i m_i} \tag{1.4}$$

where $P_{i,mass}$ is the mass-based partitioning factor, n_i is the amount of product i, and m_i is the mass of the same quantity. Using mass-based allocation, the inventory results from the data in Fig. 1.2b can, with some extra effort, be calculated as:

$$m_E = 2 \times \frac{1}{1+0.5} + 1.5 \times 3 \times \frac{1.5}{1.5+4.5} + 6 \times 1 \times \frac{6}{6+5} \approx 5.7\text{gE / kg product} \tag{1.5}$$

As can be seen, the introduction of by-products reduces the amount of emission allocated to the main product, since the by-products take a share of the burdens.

In partitioning based on economic value, emissions and resource use are often allocated to by-products based on their market price (Guinée et al. 2004). The rationale for using economic allocation is that the economic value often is the main driver behind the production of products and by-products, with the economic value then reflecting the extent to which the by-product causes the production and associated emissions (Ardente and Cellura 2012). Analogous to Eq. 1.4, the economic allocation is conducted as:

$$P_{i,econ} = \frac{n_i x_i}{\sum_i n_i x_i} \tag{1.6}$$

where $P_{i,econ}$ is the economic value-based partitioning factor and x_i is the economic value of product i.

Note that even the flow chart in Fig. 1.2b is much less complicated than those of most LCA studies. In particular, introducing multiple inputs flows to processes and considering loops (e.g., due to recycling) soon make the calculations too complicated to be performed by hand. To aid the calculations of the LCI for such more complicated product systems, different softwares are available to aid the calculations, ranging from spreadsheets in Microsoft Excel to dedicated LCA software such as SimaPro, GaBi, openLCA, Umberto, and CMLCA.

Once the complete LCI has been calculated, results are typically presented in the form of inventory tables. These contain the various emissions and resources used related to the functional unit of the study. In Fig. 1.2 example, only one emission is included, which would make a very short inventory table. Instead, Table 1.2 shows a hypothetical example of an inventory table with more emissions and resources used, including emission E as one among several. Note that in real-world LCA studies, inventory tables are typically much longer.

Table 1.2 Example of an inventory table for a hypothetical case with a functional unit called FU

Flow	Quantity	Unit	Note
Output: Main product			
Product	1	FU	–
Output: Waste			
Solid waste	1700	kg/FU	To landfill
Liquid waste	69	liter/FU	To incineration
Output: Emissions			
Emission A	14	kg/FU	To air
Emission B	0.50	g/FU	To air
Emission C	23	g/FU	To air
Emission D	65	g/FU	To water
Emission E	12.5	g/FU	To water
Emission F	0.21	g/FU	To water
Emission G	4200	g/FU	To water
Emission H	130	mg/FU	To soil
Input: Resources			
Resource R	13	kg/FU	–
Resource S	500	kWh/FU	–
Resource T	4200	kg/FU	–
Resource U	9.8	kg/FU	–
Resource V	2.5	MJ/FU	–

Under “Note,” various different types of information can be added, including also data sources

2.4 Interpreting Results and Drawing Conclusions

Although the interpretation of LCA results is generally done after the LCIA phase, some preliminary interpretations can be done already after the LCI analysis. An early hotspot analysis can be conducted to identify the most major energy and materials inputs. For example, in Table 1.2, resource T has the by far largest input flow by mass to the product system. Regarding energy use, resource S seems to be dominating. Aggregated inventory indicators can be applied or developed to facilitate hotspot analysis on an inventory level (see further Chap. 9). For emissions, emission A is the largest contributor by mass (Table 1.2). However, this type of hotspot analysis is of more questionable value for emissions considering their large differences in impact per amount emitted for some impact categories. The toxicity potential is perhaps the most extreme case here, for which differences in impact per amount emitted can be larger than 10 orders of magnitude between substances. The impact of the mass-wise smaller emission E might thus have a much larger toxicity impact than the mass-wise larger emission A.

Another valuable type of interpretation that can be done already at an inventory level is comparing similar product systems to identify differences in inputs and outputs. Such differences can reflect variation in process setup and/or performance, which might become more difficult to identify once the inventory results have been characterized in the LCIA phase. To take a recent example, Furberg et al. (2019) conducted a partial inventory-level comparison between their results for tungsten trioxide (WO_3) production and the results from Syrrakou et al. (2005) (Table 1.3). As can be seen, for the inputs included in the comparison, most are used at similar amounts. The exceptions are sodium hydroxide, where the difference is about a factor of seven, and sulfuric acid, where the difference is about a factor of three. Although the exact reason for these differences was not discovered, it was noted by Furberg et al. (2019) that these two inputs are connected: the sodium hydroxide is partly used neutralize the sulfuric acid. The reason behind the differences could thus be due to different assumptions about the use of sulfuric acid and/or the need for

Table 1.3 Example of an inventory-level comparison between two LCA studies

Input	Furberg et al. (2019)	Syrrakou et al. (2005)
Aluminum sulfate	0.08	0.08
Magnesium sulfate	0.03	0.03
Sodium carbonate	1.2	1.4
Sodium hydroxide	**0.14**	**1.0**
Sodium sulfide	0.07	0.05
Sulfuric acid	**0.56**	**1.4**

Modified from Furberg et al. (2019). The two inputs for which differences are most notable are highlighted in bold. Unit: kg input/kg WO_3

acid neutralization. The comparison thus provides a starting point for deciphering the differences in results.

Another reason for comparing inventory-level results is to investigate whether the same processes have been considered between different studies in cases where this is poorly reported. If the inventory-level inputs and outputs are widely different, there is a high chance that different processes where considered.

3 Environmentally-Extended Input-Output Analysis

Although the process LCI approach described in Sect. 2 is probably by far most common for conducting the calculations of the LCI analysis phase, there is an alternative approach called environmentally-extended input-output analysis (EEIOA) (Nakamura and Nansai 2016; Suh and Huppes 2005). It will not be given much further attention in this book but is described briefly here. The basis for this approach is that there exist economic accounting data worldwide that describes the trade between countries and economic sectors. For example, it is noted in economic accounting when 1000 kg iron ore is imported to the Norwegian construction sector from Sweden. This data thus covers many of the global trade flows. Notably, they also cover flows that are typically not included in the process LCI approach, such as flows related to services, public administration, and social work. Furthermore, some forms of cutoffs are always made in process-based LCI analysis, consciously or not, for example, of inputs that are too minor to show up in the data. The omission of these types of flows in the process LCI approach can be referred to as the truncation problem, which results in a truncation error of the process LCI approach relative to the actual emissions and resources used. This truncation error (ε) can be estimated as (Ward et al. 2017):

$$\varepsilon = 1 - \frac{I_p}{I_{tot}} \tag{1.7}$$

where I_{p} is the environmental impact as obtained from a process LCI analysis and I_{tot} is the estimated total impacts. Estimations of the magnitude of the truncation error range from a few percent to as much as 100% of the impacts depending on the product and estimation method (Ward et al. 2017), indicating that the truncation error can indeed be substantial. These estimations support the use of the EEIOA approach since it presumably captures a larger share of the impacts resulting from emissions and resource use. The trade flows can be supplemented with so-called environmental extensions, which relate the economic trade flows to emissions and resource use by assuming a proportional relationship between them. Similar to the matrix representation approach, the EEIOA makes use of matrix calculations. The inventory result is then a matrix (vector) **q** containing emissions and resource use (corresponding to the **M** matrix in Eq. 1.6) associated to a demand **y** (Suh 2004):

$$\mathrm{q} = \mathrm{B}\left(\mathrm{I} - \mathrm{A}\right)^{-1} \mathrm{y} \tag{1.8}$$

where **B** is a matrix containing all emissions and resources used (corresponding somewhat to the **B** matrix in Eq. 1.6), **I** is the identity matrix (with ones in its diagonal and zeroes elsewhere), **A** is a matrix with the inputs to sectors (having sectors both as rows and columns, corresponding somewhat to the **A** matrix in Eq. 1.6), and **y** is a matrix (vector) containing the final demand (corresponding to the functional unit or reference flow of the study, as well as to the **k** vector in Eq. 1.6).

It is possible to use the process LCI analysis approach for the foreground system of a study, where the access to detailed data is often higher, and the EEIOA for obtaining inventory data for background processes. This is referred to as hybrid LCA (Nakamura and Nansai 2016; Suh 2004; Suh et al. 2004; Hendrickson et al. 2006). With such an approach, the final demand **y** is not set to the reference flow of the entire study, but to a certain input to the foreground system from the background system. An example could be an input of electricity or a chemical such as ethanol. The emissions and resource use (the **q** vector) are then calculated for that specific input, rather than taking the background system data from e.g. an LCA database.

In addition to avoiding truncation errors, the EEIOA approach has the advantage of being faster – it can be used to conduct an LCA study within a few hours (Hendrickson et al. 2006). There are several EEIOA databases available, most notably EORA, EXIOBASE, WIOD, GTAP-MRIOT, GRAM, and IDE-JETRO (Tukker and Dietzenbacher 2013). However, not all countries are typically covered in these databases underpinning the EEIOA approach to LCI analysis, but some are rather aggregated into larger regions, such as "rest of the world Asia and Pacific" and "rest of the world Africa." Some economic sectors can also be much broader than individual products, such as "forestry products" and "textiles." The EEIOA approach thus has both benefits and drawbacks compared to the process-based LCI analysis approach.

4 Overview of this Volume

This volume of the LCA Compendium contains a number of chapters addressing central aspects to LCI analysis.

In Chap. 2, the general principles of setting up an LCI model and LCI analysis are described in more detail by introducing the core LCI model as a relatively simple, linear model, and extensions that allow addressing reality better.

Chapter 3 regards the development of unit processes, which can be seen as the very cells or atoms of LCI analysis. As shown in Chap. 3, developing unit processes of high quality and transparency is not a trivial task but is crucial for high-quality LCA studies.

Chapter 4 regards the multifunctionality problem mentioned in Sect. 2.3.

In Chapter 5, the quality of data gathered and used in LCI analysis is discussed. State-of-the-art indicators to assess data quality in LCA are described and the fitness for purpose concept is introduced: data quality is not an absolute property of a dataset, but instead depends on the application.