Attributional and consequential life cycle assessment

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Chapter

Attributional and Consequential Life Cycle Assessment

Tomas Ekvall

Abstract

An attributional life cycle assessment (ALCA) estimates what share of the global environmental burdens belongs to a product. A consequential LCA (CLCA) gives an estimate of how the global environmental burdens are affected by the production and use of the product. The distinction arose to resolve debates on what input data to use in an LCA and how to deal with allocation problems. An ALCA is based on average data, and allocation is performed by partitioning environmental burdens of a process between the life cycles served by this process. A CLCA ideally uses marginal data in many parts of the life cycle and avoids allocation through system expansion. This chapter aims to discuss and clarify the key concepts. It also discusses pros and cons of different methodological options, based on criteria derived from the starting point that environmental systems analysis should contribute to reducing the negative environmental impacts of humankind or at least reduce the impacts per functional unit: the method should be feasible and generate results that are accurate, comprehensible, inspiring, and robust. The CLCA is more accurate, but ALCA has other advantages. The decision to make an ALCA or a CLCA should ideally be taken by the LCA practitioner after discussions with the client and possibly with other stakeholders and colleagues.

Keywords: life cycle inventory analysis, methodology, attributional LCA, consequential LCA, allocation, marginal data, electricity

1. Introduction

Life cycle assessment (LCA) is the quantification of potential environmental impacts and the resource use throughout a product's life cycle: from raw material acquisition, via production and use phases, to waste management [1]. It has been frequently applied by consultants, researchers, industry, and authorities for the past 30 years. It has proven useful for gaining knowledge on the life cycle, for communication of environmental information, and for various kinds of decision-making.

Meanwhile, it was clear almost from the start that results from different LCAs can contradict each other. This is still true, despite many attempts to harmonize, standardize, and regulate LCA. From history, we learn that it is not realistic to expect LCA to deliver a unique and objective result. It should not be regarded as a single unique method; it is more fruitful to consider it a family of methods.

Attributional LCA (ALCA) and consequential LCA (CLCA) are important groups within this family of methods. The choice between ALCA and CLCA guides other methodological decisions in the LCA, such as the choice of input data and the modeling of processes with multiple products. However, within ALCA and CLCA,

there are still many decisions to be made—many versions or members within each group in the LCA family.

The purpose of this chapter is to discuss and clarify key concepts in relation to ALCA and CLCA and to guide the reader through the necessary and subjective methodological choices. The example used often relates to the supply of electricity in the life cycle, because much of the methodological debate has been on how to model electricity. The chapter is still relevant to all kinds of LCA, because energy supply is part of virtually all LCAs and because most of the discussion is valid also for modeling other parts of the life cycle. Furthermore, the chapter is relevant to other, similar types of quantitative environmental and sustainability assessments— for example, carbon footprint, which essentially is an LCA except that it is limited to emissions of greenhouse gases [2].

To structure the discussion on the pros and cons of different methodological choices, I start by establishing a set of criteria for what an LCA, or a quantitative environmental systems analysis in general, should be and do (Section 2). The ALCA and CLCA approaches are outlined in Section 3, and their implications for the choice of data and allocation problems are discussed in some detail in Sections 4 and 5, respectively. Section 6 includes an assessment of the two approaches based on previous discussions. The chapter concludes with a few recommendations for the LCA practitioner.

The LCA methodology is diverse, and the interpretation of the key concepts also varies between researchers. This chapter presents my view on the matter, which is subjective but based on knowledge gained from more than three decades of research in LCA and energy systems analysis. I present my arguments for this view but leave it to you, the reader, to accept my view or to choose another perspective.

2. Criteria for methods in environmental systems analysis

Environmental systems analysis is different from traditional science in that the aim is not just to systematically gather knowledge; it has the specific aim to gather and communicate knowledge that results in actions that reduce the negative environmental impacts of human activity in total or at least per functional unit, that is, per unit of utility that the studied system generates. The more a method for environmental assessments can be expected to contribute to this purpose, the better it is.

For a method to benefit the environment, it must be possible to apply. The results need to be reasonably accurate, possible to communicate, and perceived as relevant by decision-makers (**Figure 1**). Furthermore, the method should be resistant against abuse. Each of these criteria is briefly discussed below.

Different methods meet the criteria to varying degrees, but no method is ideal from all aspects. There will always be a trade-off between, for example, feasibility and accuracy. Hence, the set of criteria is not sufficient as a tool for objective selection of the best methods; however, it can be used for structured discussions on the pros and cons of available methods.

2.1 Feasible

To have any effect, the method must be used. The more often it is used, the more results it will generate. How often environmental assessments are made depends on how useful the results are (see Section 2.2–2.4). But it also depends on how easy the methods are to apply and how expensive the studies become. This in turn depends on how complex the methods are and on the extent to which the data and
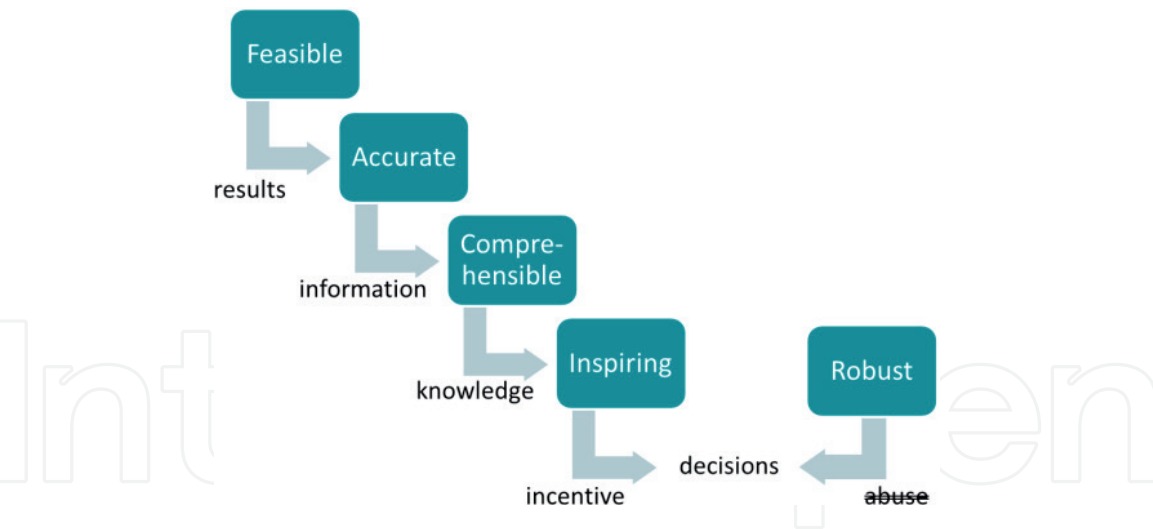
Figure 1.
Criteria for assessing methods for environmental assessment and their role in shaping decisions that are good for the environment (based on Ekvall et al. [3]).

models needed are available. The method becomes more cost-efficient and can potentially have a greater impact if the results and conclusions it generates can be generalized and reused in multiple decision situations. Hence, the method should ideally be easy and cheap to apply and generate results and conclusions that can be generalized.

2.2 Accurate

An environmental assessment is sometimes designed to guide a specific decision. To have a positive effect, the results must guide such decisions in the right direction more often than not. The greater the chance that results will point in the right direction, the better. Hence, the method should ideally generate results that are as comprehensive, accurate, and precise as possible.

2.3 Comprehensible

Besides guiding specific decisions, an environmental assessment can contribute to increasing the knowledge of experts and decision-makers. If accurate, such knowledge not only contributes to deliberate immediate actions but can also have a positive impact on future decisions. To educate decision-makers and other stakeholders, the environmental assessment must be transparent and possible to understand. Decision-makers receive a large amount of information and have limited capacity for information processing. For this reason, the method and the results it generates should be easy to communicate and understand. Communication is easier when the concepts used in the method are clear and intuitively easy to understand. Communication is more challenging when the study is very comprehensive or conceptually complex. Hence, the method should ideally result in studies that are transparent, have a simple structure, and use intuitively clear concepts.

2.4 Inspiring

In order for environmental assessment to have a positive effect, the information and knowledge they generate must result in actions. Decision-makers often have conflicting goals, and decisions are often not rational in the sense that they are based on documented facts only. To convince and inspire decision-makers, the

study should be perceived as relevant, legitimate, and credible and the recommendations clear. A study can be perceived as more relevant if it focuses on things that the decision-makers can influence and/or have a clear connection to. Legitimacy increases if the study is perceived as impartial and fair. Credibility can be obtained, for example, through sensitivity analyses. The conclusions and recommendations are clear when the uncertainties are not too great.

Relevance and legitimacy are highly subjective. They both increase if the design of the study accounts for the need for knowledge as perceived by the decision-makers. This means that the choice of methods should ideally be adapted to the situation and may vary depending on the decision-makers involved.

2.5 Robust

Robustness here means that the method gives roughly the same results regardless of who applies it. This makes the method more difficult to abuse, that is, to apply in environmental assessments with the purpose to stop or delay decisions with positive consequences for the environment or to defend decisions with poor consequences. The method becomes more robust if it does not require the user to make assumptions or subjective choices that greatly affect the results. It is also more robust if there are detailed guidelines for how the method is to be applied and/or an established good practice for the application.

3. Attributional and consequential LCA respond to different questions

As clear from the Introduction, we can distinguish between ALCA and CLCA. The distinction between two types of LCA was suggested in the beginning of the 1990s [4, 5]. It was established toward the end of the decade [6] to resolve debates on what type of input data to use in LCAs (cf. Section 4) and on how to deal with the allocation problems that occur when, for example, a process produces more than one type of product (Section 5). Various names were used on the two types of LCA [7], but the terms attributional/consequential have been used since 2001 [8].

Several different definitions of attributional and consequential LCA have been suggested [9, 10]. I prefer the definitions of Finnveden et al., in what is probably the most cited scientific paper on LCA [11]:

- Attributional LCA: LCA aiming to describe the environmentally relevant physical flows to and from a life cycle and its subsystems

- Consequential LCA: LCA aiming to describe how environmentally relevant flows will change in response to possible decisions

These definitions clearly connect ALCA/CLCA not only to methodological choices but also to the goal of the study, because they respond to different questions (**Figure 2**). An ALCA gives an estimate of how much of the global environmental impact belongs to the product studied. A CLCA gives an estimate of how the global environmental impact is affected by the product being produced and used.

Note that the latter can include both increases and reductions in the environmental impact. It is not unusual that an increase in the production of a product leads to increases in emissions as well as to environmental benefits. The production of district heating in a combined heat-and-power (CHP) plant in Sweden, for example, generates emissions from the CHP plant but reduces emissions in other parts of the electricity system, when electricity from the power plant replaces other electricity production.

There are thus two types of LCAs, carbon footprints, etc.:

- Attributional assessments, which give an estimate of what part of the global environmental burdens belongs to the study object

- Consequential assessments, which give an estimate of how the production and use of the study object affect the global environmental burdens

The choice between ALCA and CLCA affects system boundaries. In the example of district heating from a CHP plant, a CLCA includes both the emissions from the CHP plant and the reduction in emissions from the electricity production displaced by electricity from the CHP plant. In general, when a production process delivers more than one type of products, the CLCA should take into account how the process is affected by a change in the of the product investigated. If it affects the production of other products from the process, the system should be expanded to include the effect of that change.

A more advanced CLCA can also include other types of consequences. An increased use of a material in the studied system can, for example, lead to less material being used in other systems. This reduction can be quantified with a partial equilibrium model of the market [13]. The alternative use most likely to be affected can be identified through an econometric analysis [14].

An investment in a relatively new energy technology can contribute to improvements in that technology and thus to more such investments being made in the future. Such an indirect effect can in some cases be very large [15]. In an advanced CLCA, the effect could be roughly estimated using an energy system model with so-called experience curves [16].

An ALCA, in contrast, does not include environmental benefits or other indirect consequences that arise outside the life cycle of the investigated product. Instead, the raw material use and emissions of a co-production process are partitioned between the products of that process. In the cogeneration example above, the environmental burdens of the CHP plant are divided between the electricity and the heat. Such a partitioning is called allocation and can be done in several different ways (see Section 5.1).
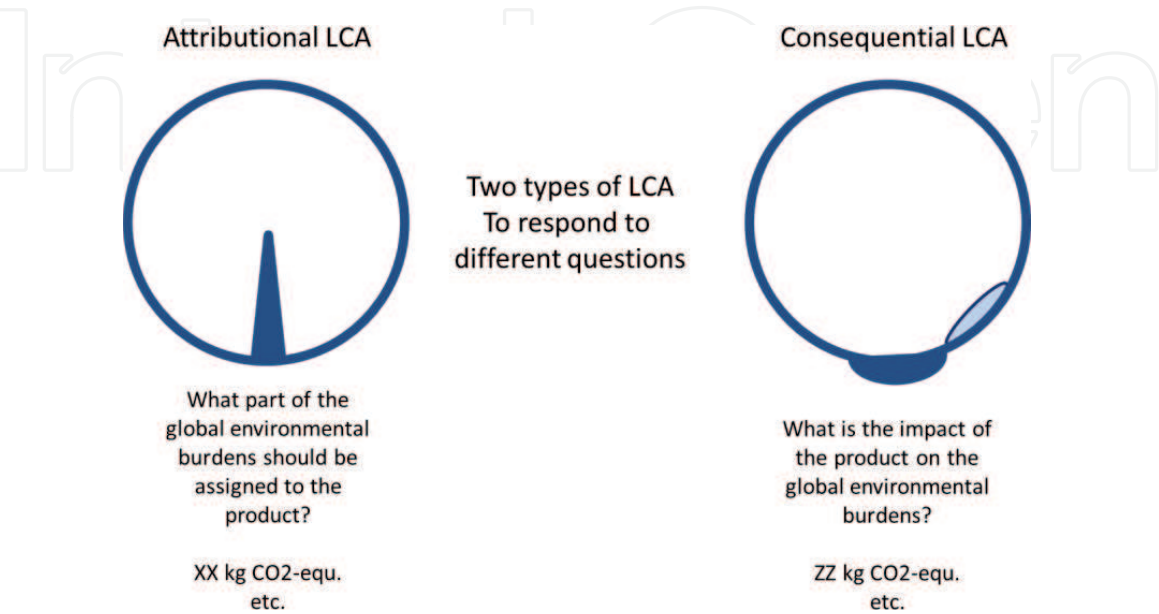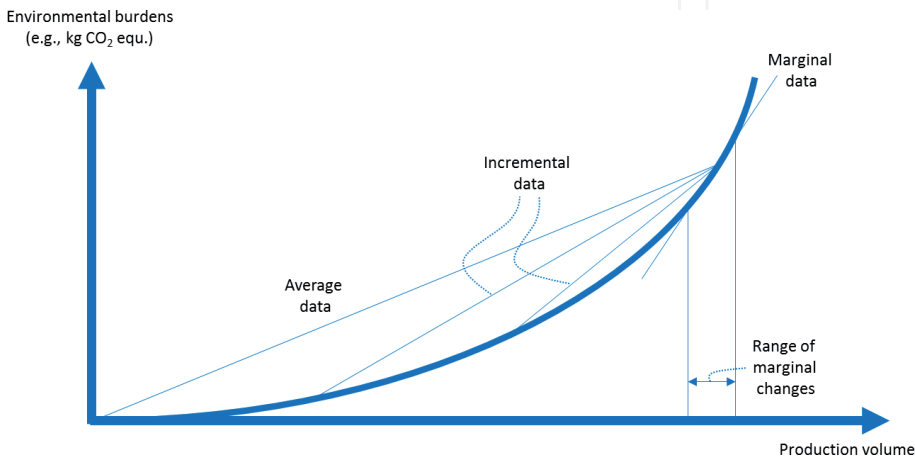

Figure 2.
Illustration of accounting and consequence LCA (based on Weidema [12]). The large circles symbolize the total environmental burdens of the world.

The choice between attributional and consequential LCA also affects the choice of input data to the calculations. An ALCA estimates how much of the world's environmental impact belongs to a product. If electricity is used in the product's life cycle, the calculations must include the product's share of the environmental burdens of the electricity production system. This is calculated by multiplying the product's electricity consumption by the average environmental burden of the electricity system per unit of electricity delivered. The figures describing the average environmental burdens are called average data. The electricity described by these average data is called average electricity.

Average data is used not only to model electricity production in ALCA. If the product investigated contains steel, average data is used to model steel production. The same applies to other input goods. In order to calculate the average environmental impact of a production system, the boundaries of the production system must be defined. This can also be done in different ways (see Section 4.1).

A CLCA aims to generate information on how the study object affects the environmental burdens of the world. If electricity is used in the system investigated, the CLCA should include data that reflects how the environmental burdens of the electricity production system are affected by this electricity use. In a few cases, the system investigated has a significant impact on the electricity production—for example, in a study of a future electric car fleet. In such cases, the CLCA should ideally be based on input data that reflects how such a large change in production volume would affect the production system's environmental burdens. Such data are called incremental data. With incremental data, the environmental burdens per kWh electricity often depend on the size of the change in power generation (compare the slope of the two lines representing incremental data in **Figure 3**).

In most cases, however, the electricity use in the system investigated is so small it has only a marginal impact on the electricity system. A change can be described as marginal when it occurs within a range where the environmental burdens as a function of the production interval can be approximated with a straight line (see **Figure 3**). Within this range, the slope of the line represents the approximate increase in environmental burdens per unit increase of electricity produced. Since the line is straight, the environmental impact per kWh is approximately constant, and the environmental impact of an additional electricity demand is proportional to the size of this demand. Data that reflects the environmental impact per kWh change within this range is called marginal data. The electricity described by marginal data is called marginal electricity.

Figure 3.
Illustration of average data, incremental data, and marginal data (based on Azapagic and Clift [17]).

A CLCA should, if possible, include marginal data not only on electricity production but also on the production of other inputs where the study object only has a marginal impact on the total production volume. There are different types of marginal effects and different ways of identifying marginal production. This is further discussed in Section 4.2.

A CLCA can be made to describe and estimate the consequences of a given decision but also to investigate what a specific decision-maker can influence. If this decision-maker can completely shut down or replace a production system, the CLCA should include the entire production system. The environmental burdens per unit produced in this system are then the total burdens of the system divided by the total product output. This is identical to the average data.

4. The choice of average and marginal data

If marginal or average data are to be used in the LCA depends on whether the study is attributional or consequential, as discussed above. However, there are several types of average and marginal data. The next question to ask is therefore what average or marginal values should be used as input in the calculations.

4.1 The average of what?

An ALCA is based on average data on the production systems in the product life cycle. In order to calculate the average environmental impact of the production systems, they must be identified, and their boundaries must be defined.

When the supplier of a material or component is known, this supplier is linked to the product through contracts and through the economic and physical flows resulting from the contracts. Established good ALCA practice is then to use as specific data as possible. These are data representing the average environmental performance of the supplier or, when possible, of the individual processes in the production plant.

In many cases the supplier is unknown, for example, because the product is not yet being produced or because the material or component is bought on a market where the actual supplier shifts over time. Here, established ALCA practice is to use average data for the relevant geographical area. Ideally, this is the area from where the good is bought and/or the area covered by the market, which might be global or regional.

Energy carriers like electricity, gas, or district heat are distributed in networks. When the suppliers are known, there are contractual links and economic flows to the supplier, but there is no clear physical flow from the production process to the user. If the contract specifies the producer, it is rather uncontroversial to use data representing a weighted average over the production plants that the supplier has in the network.

Contracts might also specify that the electricity bought is produced with a specific technology, such as wind power. In such cases, it is reasonable to use data for wind power in the ALCA. To be more specific, it is reasonable to use average data for the wind power of the producer or supplier to which the contract applies. If the deal is on wind power from a specific plant or site, average values for that plant/site should ideally be used. Of course, similar rules apply if the contract specifies that the electricity is hydro or some other specific technology, or green electricity in general.

When the electricity supplier is unknown, many influential LCA guidelines (e.g., [18–20]) recommend the use of national average data or, for very large countries, average data for regional electricity grids. This might be because electricity supply has traditionally been a responsibility of national authorities. For the past decades, electricity production has been privatized in many countries, power producers have become international companies (e.g., EDF, Vattenfall, E.ON),

electricity grids have become more integrated nationally and between countries, and electricity trade and transfer between countries have increased. This means that most electricity systems are no longer isolated national or regional grids. There are strong arguments for using average data for a larger geographical area instead. However, there are various ways to define this area. I here discuss them with a focus on Northern Europe, where I have my expertise:

Although production of electricity is increasingly privatized, the electricity sector is still to a large extent regulated by national authorities. One way to defend the use of national average data is to define the electricity system by the geographical scope of regulating authorities. Note, though, that electricity production is affected not only by national authorities but also by local authorities and by international cooperation, for example, within the European Union (EU).

Another approach is to define the geographical area by the electricity market. Since the establishment of the Nordic electricity exchange, NordPool, there is a well-established Nordic market, and the corresponding electricity system is often perceived as Nordic, including Sweden, Norway, Denmark, and Finland. As NordPool expands and the transmission capacity to other parts of northern Europe increases, it becomes increasingly relevant to regard the market as North European. There is also an EU directive aiming toward a common European electricity market, with provisions to remove bottlenecks in the electricity transfer between countries. In the future, the electricity market may be described as pan-European.

The electricity system can also be defined based on physical facts, for example, the transmission capacity between or within countries. This can be insufficient at times when a lot of electricity is produced at one place and used elsewhere. As a result, there will often be a difference in electricity price, for example, between North and South Sweden and between North and South Germany. The boundaries of the system can be defined where the transfer of electricity is limited by the transfer capacity in the grid, for example, between northern and southern Germany.

Alternatively, the electricity system can be defined as the area where the electricity network is synchronized, allowing for transfer of electricity without conversion to direct current. Conversion of electricity is a bottleneck because it is associated with energy loss. Based on this physical bottleneck, a system boundary is between Jutland and Zealand in Denmark, where the former is synchronized with continental Europe but the latter with the rest of Scandinavia.

Regardless of the geographical boundaries of the electricity system, the question remains as to whether data should apply to the average of the electricity produced in this area or whether they should apply to the average of the energy used in the area. In the latter case, imports and exports of electricity must be accounted for in the calculation of the average.

4.2 What marginal impacts?

The difference between short- and long-term marginal effects is important in a CLCA [13]. The distinction between short and long term is well-established within economic theory. Short-term effects in economics are effects on the utilization of existing production capacity that occurs before the production capacity has been able to adapt to, for example, a change in demand. The capacity itself is thus assumed to be unaffected in a short-term perspective.

When long-term effects are examined, the production capacity is assumed to completely adapt to the change in demand, to the extent that the risk of capacity shortage is the same as before the change. For the production of most goods, this means that the utilization rate of the capacity is assumed not to change. However, for electricity the long-term marginal effect of increased electricity use may include

the construction of, for example, new wind turbines that have lower utilization rates than other power plants. This reduces the total utilization rate in the electricity system, although the risk of capacity shortage is unchanged.

If the electricity use in the life cycle is small, the probability is very small that it will affect the energy system's production capacity. Electricity for lighting in a single house is, for example, a drop in the sea, compared to the total production capacity of the electricity system. The sea, on the other hand, does not consist of much else than drops. If a change in the lighting of a house happens to be what triggers an investment in a new power plant, the effect of the lighting becomes much greater than the electricity demand of the lighting. The long-term marginal effect is calculated as the expected value, i.e., the small probability times the large outcome. This expected value is 1 kWh/year changed production capacity per kWh/year change in the consumption of electricity.

The short- and long-term marginal effects can be difficult to communicate, as they are easily confused with the effects of changes made in the near or far future. However, short-term effects can arise far into the future, and long-term effects can occur in the coming decades. As an example, the long-term marginal technologies in 2020 are the technologies whose production capacity is affected by energy use in 2020. These effects may occur in 2025–2035. Meanwhile, the short-term marginal effects in 2050 relate to how a change in energy use in 2050 affects the utilization of the production facilities that exist in 2050. These effects occur during that same year and the years immediately thereafter. Short-term marginal effects of a disruption in 2050 thus arise later than the long-term effects of a disruption in 2020.

To make communication easier, the concepts short- and long-term marginal effects are sometimes replaced by "operating" and "built" margins. A draw-back of this terminology is that the term built margin is somewhat misleading: changes in production capacity are not always the construction of new facilities; it may instead be the closure of existing production facilities. The long-term marginal effects of a change in energy use in the year 2020 can include technologies in energy plants that are constructed during the period 2025–2035, but they can also include technologies in energy plants that are shut down during the years 2020–2030.

Which concepts to use depends on the context. In communication with the general public, the rough meaning of the concepts should be easily understood. Operating and built margin are good terms to use in this context. In communication with researchers in the field, however, the precision of the concepts is important. Then it is probably better to talk about short- and long-term effects. In communication with policy-makers and professional actors in the industry, the appropriate choice of words may depend on the situation and the level of knowledge of the audience.

Changing demand for a product often gives rise to both short- and long-term marginal effects: the utilization rate is affected first, and after a while the change also contributes to new power plants being built or old ones being shut down. Changing demand can also affect investments in several different technologies, and these investments can in turn affect both the utilization rate of existing plants and other, future investments. This means that the full marginal effect is complex. The complex margin in an energy system can be estimated in an optimizing, dynamic model that can account for both the short-term and long-term margin changes [21]. The complex marginal effect is then defined as the difference between the results of two model runs: one with the change in energy demand and one without it.

The complex margin is, in theory, the most correct to use for CLCAs whether the possible decisions involve changes in the short term (e.g., putting out a lamp) or the long term (e.g., changing the heating system in the house). This is because even short-term changes can produce long-term marginal effects. Investment decisions are based on assessments of the future demand and price of the product.

These assessments are, in turn, affected by the current market situation. If we increase electricity consumption this year, we might contribute to investment decisions being taken next year or the year after that.

In practice, the complex marginal effects are very difficult to estimate. It requires model calculations over the relevant time period. Model runs suggest that this time period never ends, because indirect effects occur when new production plants must be replaced far into the future [21]. Unfortunately, the uncertainty very far into the future is too great for modeling to be meaningful. The choice of time horizon in the model is subjective and depends on the time resolution in the model. If each year is modeled as a single or a handful of time slots, the model usually extends a couple or a few decades into the future [21–24]. An hour-by-hour model is more likely to cover just a single year [25], although it can still be possible to model a few years where each model year represents, for example, a decade [26].

Identifying marginal effects with an energy system model requires special expertise. There are rarely resources to develop an energy system model within the framework of a specific LCA. With the right expertise, the marginal effects can be studied in an existing model. It is, of course, even easier to use results from published model runs as a basis for assumptions about the marginal effects. Assumptions about marginal effects of electricity use in Sweden can be based on results from, for example, Hagberg et al. [26]. However, the simpler the method used to generate complex marginal data, the greater the risk that they do not reflect the marginal effects caused by the specific electricity use being studied.

Perhaps the biggest problem is that the uncertainty in complex marginal data is extremely large. Optimizing dynamic energy systems models indicate that the complex marginal effects of Swedish electricity use vary greatly depending on assumptions on, for example, investment costs, future fuel prices and policy instruments—where the two latter are highly uncertain [21]. Completely different marginal effects can occur in a single electricity scenario, depending on whether the expansion of wind power in the scenario is assumed to be driven by an increased electricity demand or by other motives [26]. A small change in the use of district heating can change the optimum development of an entire district heating system completely [24]. This illustrates that the actual effects of a small change in demand are and will remain basically unknown. An optimizing dynamic systems model can remind us of the great uncertainty, but not give much knowledge of the actual marginal effects.

Referring to the criteria in Section 2, input data on complex marginal effects make the CLCA results more accurate, but just a little—particularly if these data are from previously published model runs. Generating case-specific complex marginal data leads to a method that is difficult to use. The use of complex marginal data also makes the study less comprehensible: it is a challenge to explain marginal results from an energy system model. This makes it more difficult for decision-makers to assess the relevance and validity of the results.

If complex marginal effects are to be introduced at all in a CLCA depends on the context. In many cases, it is probably better to use a method that is easier to use and explain. The LCA practitioner and the decision-makers should then be aware that the method used is simplified and that the actual marginal effects remain unknown.

A simplified method can be limited to focusing on short- or long-term marginal effects only. Since investment and closure decisions have consequences for the environment during a long time, such effects are typically more important for the environment than changes in the use of existing production capacity. In other words, the long-term marginal effects are typically more important for the environment than the short-term marginal effects [13].

In some cases, however, a change in demand cannot be expected to have any effect at all on the production capacity. This applies if the existing production system has a significant overcapacity and closure of existing plants is not a reasonable option. It also applies if the production capacity is expanded for political or other strategic reasons, rather than to cover an expected demand for the product. A change in current Swedish electricity use might, for example, not have any effect on new investment decisions, because there is an overcapacity in the North European electricity system and because wind and solar power is still being expanded for policy and strategic business reasons. On the other hand, a change in electricity use can contribute to keeping electricity prices up or down, which can make decisions on continued investments more or less difficult. There is also a long-term political ambition to phase out coal and nuclear power. A change in electricity demand can contribute to a quicker or slower closure of such power plants. This discussion reminds us that the actual marginal effects are difficult to foresee. Different assumptions are possible, even if the environmental assessment is limited to long-term marginal effects.

Another way to simplify things is to use the five-step procedure presented by Weidema et al. [27] to identify the production technology that is affected by a marginal change in demand. This procedure involves responding to five questions:

1. Is short or long term the relevant time perspective?

2. What market is affected? Here, both a geographical delimitation and a delimitation in different market segments may be required, for example, in base- and peak-load electricity or in eco-labeled and non-ecolabel products.

3. What is the trend in demand in this market? If demand declines faster than the natural turnover rate in production capacity, long-term marginal effects are assumed to consist of closure of existing plants; otherwise they are assumed to consist of investments in new facilities.

4. Which production techniques are flexible, that is, can vary their production volume in response to market demand?

5. Which technology will be affected? If the marginal effect is an investment, it is assumed to be in the technology that is cheapest to expand. If the marginal effect is a closure, it is assumed that it is in the technology that is most expensive to utilize.

This five-step procedure can be used in CLCAs of a wide range of products. The procedure points at a single technology where the marginal effect occurs. This contributes to making the CLCA approach feasible and comprehensible—but at the cost of simplifying assumptions: that the relevant effects are either short-term or long-term rather than both, that markets and market segments can be clearly distinguished and do not affect each other, that the production volume of a technology is either completely flexible or not at all flexible, and that decisions are based solely on economic rationality. Each of these simplifications reduces the accuracy of the CLCA results. The LCA practitioner and the user of the LCA results should both be aware of this. The five-step procedure can be described as a structured way to arrive at an assumption of the marginal effects, rather than a method of identifying the actual marginal effects.

Another approach is to collect information on plans to close and/or expand the production capacity and assume that the built margin is the mix of technologies in

these plans. This is also an assumption, because plans do not always come true [28] and because some of the closure and investment decisions might be driven by policy or business strategies rather than by the demand for the product.

Assumptions about the marginal effects can, of course, be made even without a structured or formal procedure. Long-term marginal effects in the electricity system can, as the first approximation, be assumed to be electricity production in new natural gas-fired power plants, as they have an environmental performance that is better than some possible marginal techniques but worse than others. A possible sensitivity analysis can be based on data from old coal power or old nuclear power, as the closure of such power plants can be included in the long-term marginal effects and because they are near opposite ends of the scale for several important environmental impacts. Similarly, a first approximation and the extreme values can be identified for marginal production of other products.

To simply make an assumption is likely to be the easiest method to produce marginal data for the environmental assessment. On the other hand, pure assumptions make the study less accurate. They can also make the study less comprehensible in the sense that the basis for the assumptions can be difficult to communicate. If the assumptions appear arbitrary, the study also becomes less credible, which reduces the likelihood that the results inspire decisions and actions.

5. Dealing with allocation

A single production process often serves many different life cycles: diesel from a single refinery and steel from a steel mill can be used in almost any life cycle. If the production process generates a single type of product (e.g., steel), this is not considered a problem in LCA. We obtain input data to the calculations by simply dividing the total environmental burdens of the process by the total production, the functional output, of the process. The resulting input data are an average for that process and, hence, most suited for an ALCA. In a thorough CLCA we should ideally instead use input data that reflect how the environmental burdens of the process change as a result of a change in the total functional output. This is still a straightforward process, at least in theory.

A methodological problem occurs when the process generates more than one type of product or function, which are used in different life cycles. A refinery, for example, produces many different fuels and materials. A steel mill might produce residual heat besides the steel. A CHP plant produces electricity and heat. Waste incineration serves the function of treating many different waste flows and might, at the same time, generate electricity, residential heating, and/or process steam. The problem is to decide on how quantify the total functional output of the multifunctional process and, hence, how to allocate the environmental burdens of the process to the various life cycles it serves. The approach to this problem depends on whether the LCA is an ALCA or a CLCA.

5.1 Partitioning in attributional LCA

An ALCA aims to estimate what share of the global environmental burdens belongs to the product investigated. Faced with the allocation problem, the task is to estimate what share of the burdens of the multifunctional process belongs to the product investigated and also what share of input materials, energy, etc. The basis for this allocation has to be a property that the products and/or functions of the process have in common: mass, energy content, economic value, etc. The total output of the process can be

quantified in terms of this property, and the burdens of the process can be partitioned and allocated to the different products/functions in proportion to this property.

What properties the products and functions have in common varies between multifunctional processes:

- A refinery: mass, energy, exergy, and price

- A CHP plant producing electricity and heat: energy, exergy, and price

- A steel mill with residual heat: price

- Waste incineration with energy recovery: price

As indicated from this short list, the price is sometimes the only possible basis for allocation. In many ALCAs, it is the only allocation key that can be consistently used throughout the life cycle. Economic value can also be considered a valid basis for the allocation, since the economic value of the products is a proxy for their contribution to the expected profit from the process. The expected profit is typically the reason for investing and running the process and, hence, the cause of its impacts on the environment [12, 29].

Economic allocation is often criticized because it will make the LCA results vary as prices change over time. However, the LCA results can be made more stable by using the average price over a period of several years as basis for the allocation. This will also more precisely reflect the causality, because the expected profit is more likely to depend on the average price than on the price at a specific point in time.

There are cases where the economic value does not reflect a causality, because the processes are not driven by the expected profit but by concern for, e.g., the environment. These include noncommercial processes such as municipal wastewater treatment plants [30] and landfills. In these cases, the economic value is less valid and might not even be possible to use as basis for the allocation.

When we choose an allocation key, we might account for what the intended audience considers to be fair. This increases the legitimacy of the study in their eyes, which increases the chance of the LCA leading to decisions.

The choice of allocation method also depends on how feasible it is. If the allocation problem is not important for the results and conclusions of the ALCA, the easiest methods can be used to keep the cost of the study down. This can include allocating all burdens to the main product of the process—for example, to the steel from the steel mill with residual heat.

5.2 System expansion in consequential LCA

A CLCA aims to estimate how the global environmental burdens are affected by the production and use of the product investigated. Faced with a multifunctional process, the task is to estimate how the flows of the process are affected: the flows of input materials and energy, the emissions and waste flows, and the output of each product and function. When the output of products and functions for use in other life cycles are affected, the CLCA system should ideally be expanded to include the processes that are affected by this change in flows.

A change in the demand for one of the products from a multifunctional process can affect decision-makers running the process and other actors in various ways that are difficult to predict and model. To make the CLCA approach feasible, we can choose to divide the multifunctional processes into three idealized cases [13]:

1. Independent production: a change in the demand for the product investigated affects the output of this product but not the flow of other products and functions from the process.

2. Use of main product in joint production: an increase in the demand for the product investigated drives the process and increases the output of all its products and functions proportionally.

3. Use of by-product in joint production: a change in the demand for the product investigated does not affect the process or any of its outputs; instead it affects the alternative use of the by-product.

The idealized cases are simplifications of reality: products from a multifunctional process are rarely produced completely independent of each other [31], and the process is rarely driven by only one of the functional outputs.
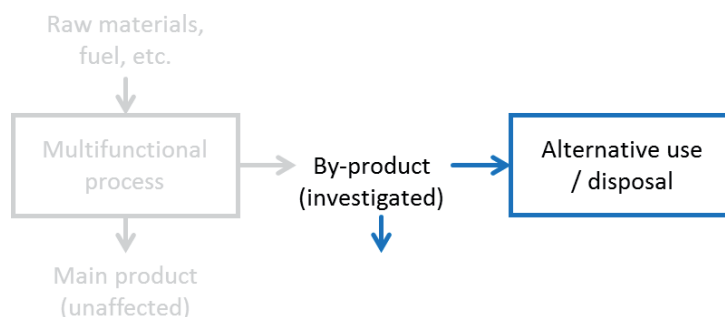
If the products of the multifunctional process are independently produced, the input data for each of the products should reflect how the environmental burdens of the process change when the production of this product changes while the production volume is constant for the other products.

If the CLCA includes the use of the main product from a joint multifunctional process, the LCA model should include this process and also the processes affected by a change in the volume of by-products. The latter are typically assumed to be the production of products that compete with and are substituted by by-products from the multifunctional process (see **Figure 4**). Since the study is a CLCA, the competing production should ideally be modeled based on marginal data (cf. Sections 3 and 4.2).

If the CLCA instead includes the use of a by-product, the operation of the multifunctional process is assumed to be unaffected by the demand for this product. The use of such a by-product does not affect its production; instead, it affects how much of the by-product is available for other purposes. The CLCA model should include affected processes only, which means it should not include the multifunctional process. Instead, the model ideally includes the marginal, alternative use of the
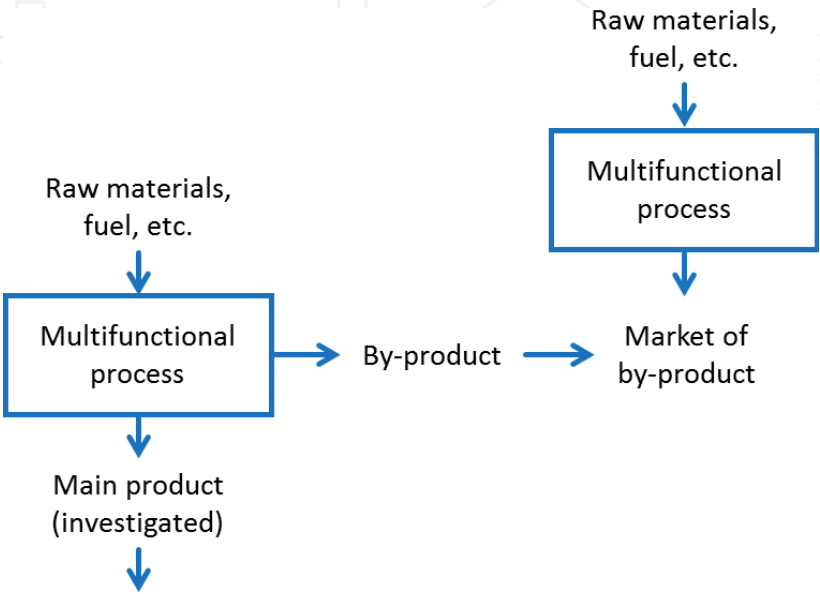
Figure 4.
System expansion at a joint multifunctional process where the product investigated is the main product (based on Ekvall and Weidema [13]).

Figure 5.
System expansion at a joint multifunctional process where the product investigated is a by-product (based on Ekvall and Weidema [13]).

by-product. This is the use affected by a (usually marginal) change in supply of the by-product (**Figure 5**).

In some cases, the by-products are not fully utilized: for example, part of the residual heat from a steel mill might be cooled off, and part of a residual material might be disposed as waste. In such cases, a change in the use of the by-product is not likely to affect the alternative use but instead how much of the by-product needs to be cooled off or disposed of in some other way. The CLCA should include the affected disposal process.

Note that the "expanded" system in **Figure 5** is not necessarily larger than the original system. It does not include the multifunctional process or the production of fuel and other raw materials for that process. Instead, it includes the disposal or alternative use of the by-product and any foreseeable consequences thereof.

The easiest method, such as ignoring the production of by-products, can be applied in the CLCA if the choice of approach is not important for the results and conclusions of the study. However, more information is required to decide on such a cut-off in a CLCA, compared to an ALCA. Even if a multifunctional process has little environmental burdens, making it unimportant in an ALCA, a change in this process might have environmentally important consequences elsewhere, hence making it significant for the CLCA.

6. The pros and cons of attributional and consequential LCA

Attributional and consequential LCA have both advantages and disadvantages [9, 32]. This section discusses the choice between ALCA and CLCA using the criteria described in Section 2. The intention is not to determine what kind of LCA is superior but to discuss and explain their strong and weak aspects. The intention is also to show how the criteria in Section 2 can be used systematically to structure a discussion and assessment of methodological options.

6.1 Feasible

In a CLCA, the system model often needs to be expanded (Section 5.2), which requires environmental data on more processes and also economic data on the markets affected by the production and use of the product investigated (cf. Section 4.2). The databases that exist today usually include average data, but few include marginal data—Ecoinvent 3 is a notable exception, although its marginal data are rough. All of this means that a CLCA risks becoming unfeasible or at least significantly more expensive than an ALCA. On the other hand, the CLCA can exclude parts of the life cycle that are not affected by the production of by-products

(cf. Section 5.2). The cost of CLCAs can also be reduced by limiting the study to the consequences expected to be the most important for the conclusions.

With time, CLCAs may become easier to carry through if future databases include more of marginal data.

6.2 Accurate

A CLCA generates information on the environmental impact of a specific decision or information on how a decision-maker can affect the environment. This is just the accurate information to have as a basis for decisions that contribute to reducing the total negative environmental impacts or, at least, the impact per functional unit.

An ALCA might be more precise and comprehensive, because a detailed and comprehensive CLCA might be too expensive or even unfeasible to carry through (see Section 6.1). As an ALCA is refined, it becomes more detailed, and the results converge toward an exact response to the attributional question: how much of the world's environmental impact belongs to the product studied? However, even a very precise answer to this question will in some cases guide decisions in the wrong direction, because the impacts belonging to a product are not the same as the consequences of producing and using this product (see **Figure 2**).

Refining a CLCA can involve accounting for more causal relationships. This makes the CLCA more comprehensive, but it does not necessarily mean that the results converge toward a final answer. On the contrary, as an additional causal relationship is included in the calculations, the results might shift completely and point in another direction.

The CLCA provides, by definition, more information on how decisions affect the environment; however, if the CLCA results are highly uncertain and do not converge toward a final, true result, the CLCA might not guide decisions in the right direction more often than an ALCA.

6.3 Comprehensible

An ALCA is based on the concepts "life cycle" and "value chain" which are intuitively clear and easy to communicate. The system model in an ALCA usually has a simple structure, which means that it can easily be presented in a way that is transparent, at least in principle. The high level of detail that can be achieved, how-ever, makes the study bulky and can make it a challenge in practice to communicate to decision-makers and other stakeholders.

The basic concept in a CLCA is "consequences." This is also intuitively easy to understand. However, other concepts required to understand the study (marginal production, partial equilibrium, etc.) are more difficult to grasp. The system model is also more complex with environmental burdens, avoided burdens, and additional, indirect burdens and with models of markets between the models of production processes. Making such a study comprehensible to decision-makers and stakeholders can be very difficult.

6.4 Inspiring

An ALCA can be interpreted to distribute responsibility and guilt for environ-mental impact, and recognition and goodwill for environmental improvements in the value chain, a part of the technological system that is linked to the production and use of the product through contracts and/or physical flows. An LCA model based on such clear links can be perceived as a relevant basis for choosing between

products and for decisions on changes in the product. If the choice of allocation methods and system boundaries is accepted by the decision-maker, the results will also be perceived as fair and legitimate. However, they can be questioned by actors who have other, subjective perspectives on what is fair and right.

The fact that a CLCA provides information on how possible decisions affect the environment can also be perceived as very relevant to the decision-maker. Rational decision-making requires information on the consequences of the decision. However, the CLCA typically include indirect consequences occurring in processes to which the product is not linked through physical flows or contractual obligations. The decision-maker might not want to be held responsible for such consequences. In order to account for them anyway, the decision-maker probably needs to be driven by the desire to actually improve the environment, rather than simply getting recognition for good environmental performance.

6.5 Robust

The ALCA practice is more well-established than CLCA. Environmental product declarations, a specific application of ALCA, also have detailed guidelines specifying the method [19]. In other applications, ALCA requires subjective choices of system boundaries (Section 4.1) and allocation methods (Section 5.1). However, the ALCA results are somewhat less sensitive to subjective choices than CLCA where the results might shift from positive to negative depending on system boundaries and assumptions. All this implies that ALCA is more robust and more resistant to abuse in the sense that the results depend less on who is doing the study.

The actual consequences of a decision are almost always highly uncertain. If the sensitivity analysis of a CLCA takes full account of the great uncertainty, the study will rarely reach clear conclusions. This increases the risk of decisions and actions not being taken, especially if the actions are expensive or undesirable in other ways. The large uncertainty in the actual consequences makes it easy to misuse CLCA results to cast in doubt environmentally desirable decisions.

However, when the ALCA is completed, the results can be abused if presented as a basis for decisions. This is because the ALCA does not aim to investigate the consequences of the decision on the environment. In a country with little fossil-based power production, such as Norway or Sweden, an ALCA can, for example, conclude that energy efficiency is not important for electric appliances. It can also indicate that residential heating should be provided through heat pumps rather than district heating from CHP plants fired with natural gas and perhaps even biofuel. A CLCA would not be likely to produce such results. If and when CLCA practice becomes more established, it will also become somewhat more difficult to abuse.

7. Conclusions

Attributional and consequential LCA respond to different questions: what part of the global environmental impacts is associated with the product investigated, and how does the product affect the global environmental impacts? In most applications and for most study objects, the choice between ALCA and CLCA is open. Since the two types of LCA have different advantages and disadvantages, it cannot be unequivocally stated that one is better than the other [32]. Roughly stated, the CLCA is more accurate, while ALCA have advantages when it comes to all other criteria. However, what kind of study is easiest to understand and most inspiring will vary between different decision-makers.

To ensure that the study is perceived as relevant, it is a good idea to, if possible, discuss the goal and scope of the study with the client before deciding on what type of LCA to carry through. To make the study as legitimate as possible, it might also be useful to discuss with other stakeholders. In such a discussion, it is important to carefully explain what type of information is provided by an ALCA and a CLCA. **Figure** 2 can be used in that explanation. It is also important to make clear the limitations of the different methods. Only then can the client and other stakeholders decide on the type of study they want.

As should be clear from this chapter, the actual effects of a decision on the global environmental impacts are in most cases highly uncertain. We will never know how close the CLCA results are to reflect the actual consequences. For this reason, CLCA should probably not be presented as a method to estimate the actual consequences. Instead the results are the consequences foreseeable within the methodological framework we choose to use in the study.

The risk that the study will be abused will also vary from case to case. Here, it does not help to consult the client. The LCA practitioners must instead use their own judgment and decide what kind of LCA is the most appropriate. In this decision, it may be good to consult with colleagues and/or to discuss with other stakeholders. The decision to make an ALCA or a CLCA should therefore be taken by the LCA practitioner after discussions with the client and possibly with other stakeholders and colleagues.

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