Deepening the uncertainty dimension of environmental Life Cycle Assessment: addressing choice, future and interpretation uncertainties.

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1.
General Introduction

This chapter contains several extensive quotations from:

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1.1 On Life Cycle Assessment

Over time, the importance of addressing environmental problems has become evident. For instance, a key moment evidencing the ecological impacts of pesticides used in agriculture took place in 1962 with the publication of "Silent Spring" (Carson 1962). Also after 1962, the evidence continue to grow, for instance by the work of the Club of Rome (Meadows et al. 1972), the subsequent environmental assessments (such as the Millenium Ecosystem Assessment 2005) and the work on specific problems such as the assessments by the Intergovernmental Panel on Climate Change (IPCC 2014) and by the United Nations Environment Programme (UNEP) on biodiversity (CBD 2012). In order to formulate effective response strategies, tools are needed to assess the impact of human activities on the environment. Such tools deal with relevant aspects such as the different temporal (e.g. past, present and future), geographic (e.g. local to global) and economic scales (e.g. product, sector). An important tool is Life Cycle Assessment (LCA) that emerged as a method to assess environmental impacts along value chains of products in the 1970s. The LCA tool, however, really developed in the past 30 years (Guinée et al. 2011). LCA is nowadays a standardized and broadly accepted method to understand and address the environmental impacts associated with the life cycle of a product (ISO 2006). The method, however, continuous to evolve in response to new societal questions.

LCA addresses different questions related to the potential environmental impacts through a product's life cycle. This includes extraction of natural resources, production of materials and the product itself, the use of the product, and the end-of-life treatment when it is discarded (Guinée et al. 2002). An essential element of LCA is the cradle-to-grave coverage of the product life cycle, although in some cases the scope can be different. In general, LCA can help to identify improvement opportunities in relation to the environmental performance of products (ISO 2006). Performing an LCA can also support the selection of relevant indicators and measurement techniques to track environmental performance of product-systems as well as support the implementation of marketing schemes by providing an evidence basis for claims related to product environmental performance (ISO 2006). Finally, LCA can also be useful in comparing alternatives of similar products (Guinée et al. 2002), which is one of the most popular applications of LCA.

An LCA study has four phases: a) the goal and scope definition, b) the life cycle inventory analysis, c) the life cycle impact assessment and d) the interpretation phase (ISO 2006). During the goal and scope the aim, topics, basis for comparison and calculation (the functional unit) and intended use of the study are defined. Also, the scope including the product-system boundaries and the level of detail are defined. The life cycle inventory (LCI) analysis phase is the most data intensive and consists of collecting the inventory data, i.e. the inputs and outputs of each unit process related to the product-system analyzed. The result of the inventory analysis is typically a table with the quantified inputs from and output to the environment for each of the alternatives. The life cycle impact assessment (LCIA) aims to convert the inventory results to contributions to selected impact categories such as climate change, acidification, human toxicity, etc. Finally, the interpretation is the phase in which the results calculated in the LCI and LCIA are analyzed and synthetized in the light of the goal and scope of the study. As part of this phase techniques like contribution, perturbation, and uncertainty analysis can be applied. According to the Handbook on Life Cycle Assessment (Guinée et al. 2002 p.116), uncertainty analysis helps to "…assess the robustness of the overall LCA results with respect to variations and uncertainties in the methods and data used". LCA can suffer from uncertainty introduced by different sources, a topic that will be elaborated in detail in the following sections as it is the core of this thesis.

1.2 On the uncertainty dimension of Life Cycle Assessment

Certainty is the idea of confidence, assurance and accuracy about our knowledge of the truth. "Certainty and truth exist" (Briggs 2016, p.2), evading discussions on philosophical skepticism that are self-defeating as denying their existence is already accepting a truth with certainty (Briggs 2016). The idea of uncertainty is based upon the existence of truth by acknowledging there is something that is but cannot be fully known. Uncertainty does not exist in objects themselves, aside from the sense of existence, but only in our mind or intellect (Briggs 2016). Therefore, it is our incapacity to know the truth that underlines uncertainty. For a further discussion about the philosophical basis of uncertainty, we here refer to Box 1. The theme of this thesis is about how to deal with different sources of uncertainty in LCA, recognizing, acknowledging and quantifying as far as possible, different sources of uncertainty currently not yet properly captured by LCA (Box 1).

Uncertainty has been researched for about 30 years in LCA. The increased attention that LCA received during the 1990s as a tool to describe environmental impacts of products in the broad sense, came along with criticism about the drawbacks of this decision support framework used by governments and companies (Udo de Haes 1993). One of the major limitations is the importance of uncertainty (Finnveden 2000; Ross et al. 2002), which threats the reliability of decision makers on the results and recommendations from LCAs. Guinée et al. (1993 p.89) mentioned that: "A valuation of environmental profiles without an assessment of the reliability and validity of the results, is of little value". There are many ways to treat uncertainty but probability is one of the most used ones. Probability is the language of uncertainty that explains the limitations in our knowledge of the truth (Briggs 2016). This is why many fields of knowledge have relied on probability to help treat this limitation and the field of LCA is no exception.

Some of the first publications dedicated to uncertainty treatment in LCA appeared during the 1990s. Uncertainty analysis in LCA was defined by Heijungs (1996 p.159) as "the study of the propagation of unintentional deviations" in order to understand "those areas where product and process improvement lead to the highest environmental gain". Similarly, Huijbregts (1998) identified the usefulness of uncertainty analysis in LCA to help decision makers judge the significance of the differences in product comparisons, options for products improvements or the assignment of eco-labels. Weidema and Wesnæs (1996) were the first to describe and apply Data Quality Indicators (DQI), semi-quantitative numbers providing information about the quality of the data, and Data Quality Goals (DQG), the desired quality of the data, in an LCA context. This methodological development known as the "pedigree-matrix" in LCA jargon, inspired by the purely qualitative proposal of Funtowicz and Ravetz (1990), is one of the most widely applied techniques to semi-quantitatively address uncertainty of data in LCA. This method was later incorporated in the ecoinvent database (Frischknecht et al. 2007). DQIs enabled early probabilistic approaches to account for data uncertainties and LCA models evolved from deterministic, point-value models to stochastic models characterized by probability distributions (Kennedy et al. 1996).

Box 1. Broad framework of definitions for uncertainty types

Broad kinds of uncertainty have been recognized in literature. Wynne (1992 p114), identified four kinds of uncertainty in environmental sciences departing from risk assessment:

- Risk – "The system behavior is well known" as well as the chance of different outcomes.
- Uncertainty as conventionally described – Parameters are well known but not their distributions. Uncertainties are recognized and explicitly included in the analysis.
- Ignorance – It is a characteristic of the linkage between knowledge and commitments based on it. "It bets on the completeness and validity of that knowledge."
- Indeterminacy – Emerging from the question of "whether knowledge is adapted to fit the mismatched realities of application situations, or whether those situations are reshaped to 'validate' the knowledge."

Such different types, particularly, ignorance and indeterminacy are specified to emphasize that uncertainties are not always due to incomplete scientific knowledge. Uncertainty can also emerge from indeterminacies, sometimes socially driven, which can lead to questions around the validity of a theory or model under new realities such as new conditions and situations (Wynne 1992; Compare also: Ravetz 1999; Stirling 2010; Castree et al. 2014). Related to the indeterminacies, Rotmans et al. (1994) and Tukker (1998) identified paradigm uncertainties which are related to the fact that a problem may be defined and analyzed from different scientific perspectives, an issue particularly important in the context of policy support. Further, Walker et al. (2003) identified three dimensions of uncertainty each of which has its own related sources of uncertainty some of which are recognized in Van Asselt and Rotmans (2001):

- Location of uncertainty – where does uncertainty manifest within the model?
- Level of uncertainty – at what level does uncertainty manifest within the spectrum from deterministic to total ignorance?
- Nature of uncertainty - is uncertainty due to imperfect knowledge or due to inherent variability?

This thesis is placed within the space of risk and uncertainty, recognizing, acknowledging and quantifying (where possible) sources of uncertainty for LCA models beyond the deterministic and total ignorance extremes of the level of uncertainty, and refers to uncertainty manifested in the parameters, choices and imperfect knowledge of the future in LCA. This means that total ignorance and indeterminacies and their related types of uncertainties, are not explicitly studied and discussed in this thesis, which does not mean that these do not exist. In fact, as the underlying principle of this thesis is recognition and acknowledgement, we emphasize that not all can be known neither quantified.

Yet only until the end of the 1990s and beginning of the 21st century, a general framework that distinguished various types of uncertainty and variability in LCA was proposed and further studied (Huijbregts 1998a; Björklund 2002). These frameworks are of particular importance as they differentiate various types of uncertainty and variability in LCA as well as recognize that different types of uncertainty and variability might require different treatment. The types of uncertainty and variability are (according to a combination of Huijbregts, 1998 and Björklund, 2002 and excluding those types of uncertainty not further treated in this thesis as explained in Box 1):

- Parameter uncertainty: data inaccuracy, data gaps and unrepresentative data
- Uncertainty due to methodological choices
- Model uncertainty
- Epistemological uncertainty
- Spatial variability
- Temporal variability

- Sources and objects variability
- Mistakes

While uncertainty refers to a lack of knowledge about the truth (Briggs 2016), variability makes reference to inherent differences within a population attributable to natural heterogeneity of values (Björklund 2002). Therefore, while uncertainty can be reduced, variability cannot be reduced but only better estimated for instance, with better sampling (Björklund 2002).

1.2.1. Types of uncertainty in LCA

There are different uncertainty types which have their origins in different unknowns within LCA. In this thesis the definitions and classifications of Björklund (2002) for the different uncertainty types are used.

- Parameter uncertainty has been associated to data inaccuracy (Huijbregts et al. 2001), unavailability and to unrepresentative data (Björklund 2002). This is uncertainty due to for example, wrong inventory data, missing data or the use of data that refers to different technologies, places or temporal resolutions other than the intended one. This is the most known source of uncertainty in LCA as well as the most treated in the literature.
- Methodological choice uncertainty is due to the unavoidable choices of practitioners along the phases of LCA. For example, the choice of functional unit, product-system boundaries (Tillman et al. 1994), allocation methods (Weidema 2000; Guinée and Heijungs 2007), environmental impact categories, and characterization methods and factors (Huijbregts 1998b; Finnveden 1999) are typical examples of practitioners' choices while undertaking an LCA. It has been shown for various applications that different choices lead to different, and in some cases significantly different LCA results.
- Model uncertainty refers to simplification aspects of LCA such as aggregation, and the modelling aspect of LCA for example linear and non-linear models (Heijungs and Sun 2002), derivation of characterization factors (Björklund 2002) or estimation of emissions with exogenous specialized models. Model uncertainty has not been widely addressed in LCA.
- Epistemological uncertainty emerges from the lack of knowledge on system behavior for instance, when modelling future systems (Björklund 2002). The word epistemology has its origins in the Greek epistanai which means "to understand", "to know" and it has been defined as "the study or a theory of the nature and grounds of knowledge especially with reference to its limits and validity" (Merriam-webster 2015). This is probably the least addressed source of uncertainty in LCA.

- Variability refers to intrinsic fluctuations of a numerical property (Björklund 2002) such as the yield of a hectare of arable land. Variability has been widely addressed in literature mostly in relation to input and output data used in LCA. Variability is also referred to as ontic uncertainty i.e. natural randomness often expressed with means and their ranges likelihood (van Vuuren 2007)

1.2.2 Approaches to deal with uncertainty in LCA

Different types of uncertainty in LCA may require different types of treatment. There are different approaches to deal with uncertainties in LCA. In certain cases, the aim is to reduce uncertainty in order to generate a more reliable assessment and therefore, better support for decision-making. In other cases, the aim is to reflect the uncertainty of the result as an extra piece of information to the decision-maker. In general, the main approaches to different types of uncertainty are (Heijungs and Huijbregts 2004): the scientific, the constructivist, the legal and the statistical approaches. These approaches use additional research, consensus or agreement, authority, and probability and statistics to deal with uncertainty. From these approaches, only the statistical approach explicitly incorporates uncertainty in the outcomes of LCA (Heijungs and Huijbregts 2004).

Statistical approaches to parameter uncertainty have led, in the past decade mostly, to sophisticated methods to characterize input uncertainties (Heijungs and Frischknecht 2004; Bojacá and Schrevens 2010; Ciroth et al. 2013; Henriksson et al. 2013; Muller et al. 2016; Qin and Suh 2016), to propagate such uncertainties through the LCA model (Imbeault-Tétreault et al. 2013; Groen et al. 2014; Heijungs and Lenzen 2014; von Pfingsten et al. 2017), to interpret outputs with uncertainty (Heijungs and Kleijn 2001; Prado-Lopez et al. 2014, 2016; Henriksson et al. 2015a; Cucurachi et al. 2016) as well as to approaches that deal with all the above (Hung and Ma 2009; Andrianandraina et al. 2015; Gregory et al. 2016; Wei et al. 2016). Statistical and mathematical approaches to treat methodological choice uncertainty have been proposed too (Cruze et al. 2014; Jung et al. 2014; Hanes et al. 2015). These incorporate in the outcomes, the effects of uncertainty due to the different choices. Statistical and scientific approaches have also been published for model uncertainties (Padey et al. 2013; Andrianandraina et al. 2015). Typically, these treat parameter and model uncertainty simultaneously.

The composition approach (i.e. constructivist approach in Heijungs and Huijbregts, 2004) and legal approach are based on consensus among stakeholders on the choices or on predefining (ISO 2006) or mandating the choices. This reduces uncertainty in the outcomes (Heijungs and Huijbregts 2004) and increases comparability of studies yet no information on the likelihood of the results can be provided. Environmental Product Declaration (EPD) schemes as well as Product Category Rules (PCRs) are examples of such approaches to deal with uncertainty due to choices (Del Borghi 2013).

Dealing with uncertainty due to methodological choices in LCA has mostly been handled by the legal approach.

The scientific approach has mostly focused on scenario modelling as a tool to deal with different sources of uncertainty. Among these there are uncertainty due to choices (Guinée and Heijungs 2007), epistemological uncertainty (Spielmann et al. 2005; Dandres et al. 2012; Hertwich et al. 2015; Gibon et al. 2015) and parameter variability and model uncertainty (van der Harst and Potting 2014; van der Harst et al. 2014). Further, there is a large body of literature in LCA that focus on sensitivity analysis which is a way to address uncertainty due to different assumptions for parameters, methodological choices, models, etc. usually assessing their change one at the time.

In summary, within the different approaches, varied tools to deal with different sources of uncertainty in LCA are available (Table 1).

Table 1. Main sources of uncertainty in LCA and some techniques and methods to treat them. Adapted from Huijbregts (1998), Björklund (2002) and Heijungs and Huijbregts (2004).

Type Tools	Parameter uncertainty	Model uncertainty	Uncertainty due to choices	Epistemological uncertainty	Spatial variability	Temporal variability	Sources and objects variability
Scientific Approach							
Additional measurements	x						x
Scenario modelling		x	x	x	x	x	x
Non-linear modelling		x					
Multi-media modelling		x			x		
Composition Approach (Constructivist approach in Heijungs and Huijbregts, 2004)							
Expert judgements/ peer review	x		x				x
Rules of thumb	x						
Legal Approach							
Standardization	x		x				
Prescription of specific methods	x		x				
Statistical Approach							
Probabilistic simulation	x		x				x
Data quality indicators	x				x	x	x
Uncertainty importance analysis (Global sensitivity analysis)	x	x	x		x	x	x
Classical statistical analysis	x				x	x	x

Bayesian statistical analysis	x				x	x	x
Sensitivity analysis	x	x	x	x	x	x	x
Interval arithmetic	x				x	x	x
Correlation and regression analysis	x						x

1.3 Problem identification and aim

1.3.1 Deepening the uncertainty dimension in Life Cycle Assessment

In general, it is widely-agreed that dealing with different sources of uncertainty in LCA is a vital step to increase reliability of LCA results (Ross et al. 2002; Lloyd and Ries 2008). It has also been recognized that there is a need to further develop, within the LCA community, protocols for characterizing, propagating, and interpreting uncertainty (Lloyd and Ries 2008). However, to date the most common approach in LCAs is deterministic (Wei et al. 2015), excluding any specification of any type of uncertainty. Most recent efforts have been in the direction of recognizing and increasing the community's understanding of the different sources and of the implications of uncertainty for different LCA applications.

This thesis extends knowledge in the same direction - towards a clearer understanding of the implications of different sources of uncertainty in LCA – and further develops methods to treat them. Such effort is referred to as deepening the uncertainty dimension in LCA. The term deepening has its origins in the Life Cycle Sustainability Assessment (LCSA) framework proposed by Guinée et al. (2011). In LCSA, current LCA deepens to include other than just technological relations such as economic and behavioral relations (Guinée et al. 2011). In this thesis, current LCA deepens to deal with some sources of uncertainty which have not yet been widely or at all addressed in the state-of-the-art literature, and new tools are developed, within the approaches previously described (see Box 2 for the sources of uncertainty addressed in this thesis). These sources of uncertainty have been selected as they relate to some of the most pressing topics for the LCA community: 1) allocation method choice, 2) accounting for future socio-technical changes in prospective LCA and 3) interpretation of LCA results including uncertainty estimates. These are the specific issues addressed in this thesis.

Box 2. Source of uncertainty to be further addressed in this thesis

Source of uncertainty	Issues addressed	Approach used	Tool
Methodological choice uncertainty together with parameter uncertainty	Allocation method choice together with uncertainty due to missing data, data that refers to different technologies, places or temporal resolutions than the intended one	Statistical approach	Probabilistic simulations
Epistemological uncertainty (The future is unknown)	Accounting for future socio-technical changes in prospective LCA	Scientific approach	Scenario modelling
Methodological choice during interpretation phase of LCA	Choice of the interpretation method of uncertainty analysis results	Legal approach	Guidance/ Prescription of specific methods

1.3.2 Research questions

The aim of this thesis is to deepen the uncertainty dimension of current LCA in order to increase the reliability of LCA results for specific applications by means of addressing different sources of uncertainty not yet addressed, with methods not yet available. On the basis of the identified sources of uncertainty to be addressed, the following research questions will be answered in this thesis:

RQ1: How can parameter uncertainty and uncertainty due to methodological choices in a single alternative LCA be quantified and propagated to the results?

RQ2: What are the implications for uncertainty analysis in a comparative LCA context of quantifying and propagating parameter uncertainty and uncertainty due to methodological choices?

RQ3: How can epistemological uncertainty for prospective LCA be systematically and consistently addressed?

RQ4: Which statistical method(s) should LCA practitioners use to interpret the results of a comparative LCA, under the light of its goal and scope, when considering uncertainty?

1.4 Thesis outline

Following the research questions this thesis has been organized in four content chapters **(chapters 2-5)**, one introductory chapter **(chapter 1)** and one concluding chapter **(chapter 6)**. Figure 1 shows the outline of this thesis as well as the source of uncertainty, the LCA application, the approach and the tool developed or used in each chapter.

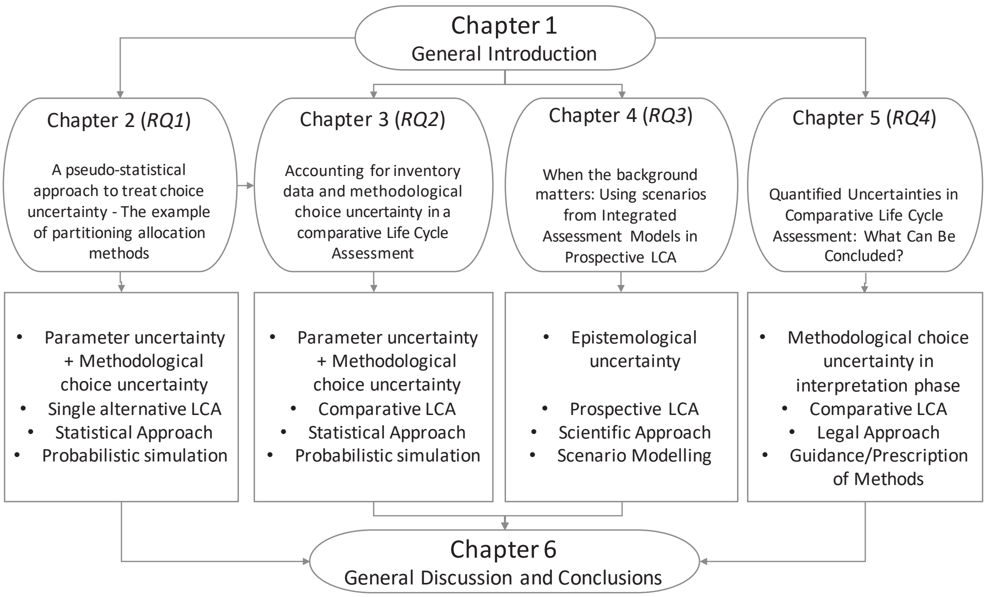

Figure 1: Outline of this thesis.

Chapter 2 develops, implements and tests a method to simultaneously propagate through LCA, uncertainty in unit process data and due to the choice of allocation methods of more than one process in the product-system. This chapter focuses on the particular example of the choice of partitioning methods for solving multi-functionality in LCA. The method developed can be used in LCA calculations and software. We assigned a methodological preference to the partitioning methods applicable to solve each multi-functional process in the foreground of the product-system, to enable pseudo-statistical propagation of uncertainty due to allocation (not strictly statistical as it is applied to choices). To illustrate the developed method and its outcomes it is applied to a single alternative LCA.

Chapter 3 broadens the application of the method developed in chapter 2 to a comparative LCA instead of a single alternative LCA. We identify the implications of broadening the scope to two alternatives with the same function. The case used in this chapter compares two aquaculture alternatives to produce fish. One of the two systems, co-produces fish with oysters, therefore, allocation of impacts becomes very relevant in this assessment to achieve comparability between the alternatives.

Chapter 4 explores a systematic and consistent approach for scenario development in prospective LCA. This approach is considered as a way to acknowledge and address epistemological uncertainty due to future socio-technical changes influencing the background of the LCA. A novel approach to systematically change the background processes in a prospective LCA is developed. It consists of deeply embedding scenarios from an Integrated Assessment Model (IAM) in the LCI of a product-system to derive future inventories based on the scenarios. The approach is applied to a prospective LCA case study comparing an internal combustion engine vehicle (ICEV) and an electric vehicle (EV) as mobility alternatives for the future. The background system addressed is the electricity production sector.

Chapter 5 conducts a critical review of methods to interpret uncertainty analysis results, particularly uncertainty-statistics methods (USM). The implications of the use of these methods for interpretation of comparative LCA results is investigated. Guidance is provided to help LCA practitioners select the most appropriate method to interpret their LCA uncertainty analysis results according to the type of goal pursued in the LCA study.

Chapter 6 reflects back on the research questions which are answered in chapters 2-5. Finally, a general discussion and a research agenda for the future are provided as part of this closing chapter