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

Mendoza Beltran, M.A.

Author: Mendoza Beltran M.A.

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6.

General Discussion and Conclusions

6.1 Introduction

LCA has become an important method to study environmental impacts of human activities. Still, there are several methodological issues in LCA that can adversely affect the reliability of results. Three of these issues relate to a) allocation, b) the representation of the time dimension and c) the interpretation of results in LCA. Uncertainties play a fundamental and underlying role for these issues. In the previous four chapters, this thesis unraveled some complexities of uncertainty analysis in LCA in relation to these three issues. This thesis aimed at deepening the uncertainty dimension of LCA i.e. provided a clearer understanding of the implications of different sources of uncertainty in LCA – and further developed methods to treat them. We departed, in the introduction chapter, from broad domains in which uncertainty has its roots. Then, the scope was narrowed down to some specific sources in the domains of risk and conventional uncertainty i.e. related to incomplete scientific knowledge and to potentially quantifiable uncertainties. The domains of ignorance and indeterminacies i.e. uncertainty related to bets on the completeness and validity of knowledge which also depends on its correspondence with the social world (Wynne 1992), were not further studied. This thesis focused on those sources of uncertainty which could be explicitly acknowledged in the results of an LCA. However, we recognized that not all sources of uncertainty can be quantified as well as not all can be known.

In particular, three sources of uncertainty related to some of the most pressing topics for the LCA community, were addressed: 1) allocation method choice (in combination with parameter uncertainty), 2) accounting for future socio-technical changes in prospective LCA and 3) interpretation of LCA results including uncertainty estimates. The choice for an allocation method introduces uncertainty in the results as different methods may lead to (significantly) different results. Also, future socio-technical changes may lead to large uncertainty of LCA results particularly for technologies or products expected to be industrially deployed in the future when socio-technical systems could look quite different compared to the present. Finally, interpretation of the results of uncertainty analysis in LCA can be done with different methods. Guidance on which method to use depending on the purpose of the LCA, was missing. These knowledge gaps have been translated into four research questions addressed in the previous chapters and which we discuss in the following sections.

6.2 Answers to research questions

Chapter 2 discussed two important sources of uncertainty in LCA: due to methodological choices and parameter uncertainty. The chapter presented and tested a method to simultaneously treat these two sources of uncertainty.

RQ1: How can parameter uncertainty and uncertainty due to methodological choices in a single alternative LCA be quantified and propagated to the results? (Answered in chapter 2)

Methodological choices are unavoidable in LCA and from all choices a practitioner has to face, the choice for allocation methods to solve multi-functionality is crucial. The allocation method selected for solving a multifunctional process can significantly change the LCA results. Parameter uncertainty is another typical issue that LCA practitioners should deal with. Parameter uncertainty can arise from different situations. For instance, when unit process datasets are not available (for the location and/or technology that the LCA study at stake deals with) and these data are then often estimated with data for other locations or technologies. Also, because unit process data can be inaccurate due to inherent measurement uncertainties. Likewise, and in many cases, because unit process data has natural variability. We proposed a pseudo-statistical protocol to simultaneously propagate parameter uncertainty and uncertainty due to the choice of partitioning methods to the LCA results. For example, in an agricultural process, uncertainty around N_2O emissions due to fertilizers application is stochastically combined with two options to allocate the emissions between the agricultural outputs with economic and mass allocation. In such way, these sources of uncertainty are propagated to the characterized results such as climate change in kg of CO_{2eq}. The protocol captures the large range of combinations resulting from sampling an allocation method per multi-functional process and a data value per process parameter in a product-system. While the choice of allocation method refers to a discrete choice described by the methodological preference of each allocation method, parameter uncertainty is better described with a probability distribution per parameter. Monte Carlo simulations were used to sample these methodological preferences and distributions, resulting in the pseudo-statistical propagation of uncertainty to the LCA results. Because the usual terms that are appropriate for data uncertainty (uncertainty, probability, statistical, etc.) are not entirely suitable for describing discrete choices, we added the qualifier "pseudo" to refer to the propagation and quantification of methodological choice uncertainty which is not, in a strict sense, statistical nor a probability applies to them as they are normative choices.

Application of the protocol to a single alternative LCA, proved that simultaneous propagation of both sources of uncertainty was possible. Yet, it also showed that absolute uncertainties only further increase in comparison to one at the time scenarios varying only the allocation method and including parameter uncertainty. This is because many (if not all) possible combinations of data and allocation methods are captured in the results (Chapter 2). Also, such results were expected because LCA integrates knowledge and uncertainty from many disciplines. However, because LCA is essentially comparative, increased absolute uncertainty of LCA results is not necessarily relevant. Thus, although the results showed an increased robustness for a single alternative LCA, the method is particularly useful for comparative LCAs in which relative uncertainties, i.e. uncertainties related to the differences between the compared product-systems, are more relevant.

Therefore, Chapter 3 expanded the application of the method developed in Chapter 2 to a comparative LCA context.

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? (Answered in chapter 3)

Applying the pseudo-statistical protocol to propagate parameter uncertainty and uncertainty due to the choice of allocation methods in a comparative LCA context has implications primarily for the sampling procedure. Because it is vital to account for relative uncertainties between the pairs of product-systems compared, paired sampling should be the experimental setup (Chapter 3). In practice, this means that for unit processes and multi-functional processes that are common to both systems, the same parameter values and the same allocation method should be sampled and used to calculate the results per Monte Carlo simulation. The LCA results of a specific simulation should be directly compared to properly reflect the comparative, or relative uncertainty. If such a setup is used, statistical significance of the difference of the environmental impacts can be sensibly determined. The difference per Monte Carlo run, for instance for the characterized results, should be used as the basis to calculate significance. In deterministic point-value LCA outcomes, it is only possible to calculate the difference of the environmental impacts for the point-value results, which usually represent specific allocation choices and average assumptions and values. The pseudo-statistical method helps addressing parameter uncertainty and acknowledge large choice-related uncertainties (on top of parameter uncertainties). It further helps in asserting if under those uncertainties alternatives are significantly different. While it might appear that alternatives are different based on deterministic LCA results, they might not be statistically different when accounting for parameter and choice uncertainty and vice versa. The case study in chapter 3 compared two technologies to produce fish. In the first only fish is produced. In the second fish is co-produced with oysters. Thus, allocation plays an important role to make the systems comparable in addition to large parameter uncertainty due to seasonal changes in the production of fish, among others. While deterministic LCA results showed that co-produced fish performs better for all impacts evaluated, including uncertainty showed that the two systems did not perform significantly different except for climate change impacts. This additional information revealed that the specific technological setup evaluated for the co-production of fish, was not having the desired mitigating effect of impacts in comparison with the current production of fish. It was concluded that production of the farm was expanded due to the additional oyster production at no additional environmental cost and with reduction of climate change impacts.

In general, and as shown in the case of chapter 3, the pseudo-statistical protocol applied in a comparative LCA context is a novel technique that can contribute to the robustness of conclusions, adding information about the statistical significance of the difference of environmental impacts between the compared product-systems. This chapter also showed that there is a practical way to estimate uncertainty beyond one at the time scenario modeling for choice-related uncertainties. Moreover, it demonstrated that for comparative assertions it is necessary to account for relative parameter and choice-related uncertainties. To determine the statistical environmental superiority of products in a robust way these are mandatory conditions. Stochastic life cycle impacts of similar products calculated separately by different LCA practitioners, and thus using independent sampling, should not be compared. Such findings may have implications for LCA guidelines for policy applications, such as the Product Environmental Footprint (PEF) from the European Commission (See section 6.3.1 for a deeper discussion on this issue).

Chapter 4 aimed to address epistemological uncertainty in prospective LCAs. To address this type of uncertainty, a novel approach to systematically change the background processes in a prospective LCA was developed and illustrated with a case study.

RQ3: How can epistemological uncertainty for prospective LCA be systematically and consistently addressed? (Answered in chapter 4)

Prospective LCA refers to forward-looking applications of LCA. Usually, they help to anticipate unintended consequences of future product-systems and help to support environmentally conscious product design. Prospective LCA should deal with large epistemological uncertainty related to the fact that the future cannot be predicted and yet the environmental performance of products is evaluated in the future. For this, assumptions should be made systematically and consistently for all relevant parameters. For instance, if one looks at the performance of combustion engine versus electric vehicles (our case studies) consistent assumptions should be made for future changes in performances of these vehicles, but also in key input parameters such as the electricity mix and therefore to all LCA parameters that depend on the electricity mix. We proposed a novel approach based on a framework for scenario development in LCA to systematically and consistently address this issue. The approach deeply embeds – conceivable as hard linking – socio-technical scenarios from an Integrated Assessment Model (IAM) with background inventory data used in prospective LCA. The IAM used in the case study is the IMAGE model. For the background inventory, we use the ecoinvent database. Combining these allowed us to derive future background inventory data based on IMAGE scenarios. To operationalize this procedure, IMAGE output (covering all sectors and world regions) is systematically fed into the inventory of ecoinvent. Systematic implementation is facilitated by the fact that the same IMAGE variables are used for all scenarios and are linked to the same ecoinvent parameters, as shown in this thesis. Since the IMAGE data is harmonized in coherent scenarios, the risk of inconsistencies is minimized.

After this procedure has been implemented and the background has been made dynamic, one is confronted with epistemological uncertainty. Linking a variety of integrated assessment model scenarios with background inventory data helped acknowledge epistemological uncertainty and lead to more robust results that accounted for varied socio-technical future paths of development. The case study of chapter 4, illustrated the method for the prospective LCA of an internal combustion engine vehicle and an electric vehicle, as two future mobility alternatives. The electricity production sector was changed using various baseline and climate mitigation scenarios (several plausible futures). As a result of the scenario linkages, the relative environmental performance of EV and ICEV over time is more complex and multifaceted than previously assumed. Uncertainty due to future developments of the electricity sector manifests differently in the life cycle impacts (e.g. climate change, particulate matter formation, etc.) according to the product (EV or ICEV), the scenario (e.g. baseline or mitigation) and the year considered. Regarding the product, uncertainty is larger for the EV, as is evident from the larger range of results, particularly in the long-term i.e. towards 2050. Nonetheless, this is only because of the contribution of electricity production to the impacts of the EV in comparison to impacts of the ICEV. Linking the scenarios for other sectors could change this outcome. For the impact categories, we observe that for climate change, particulate matter formation, and fossil cumulative energy demand, the selected IMAGE scenario has a larger influence on the future impacts of the EV. These are impacts due to GHG emissions and use of fossil fuels. Thus, baseline scenarios which have a larger share of fossil-based electricity technologies display a smaller reduction of these impacts than the original ecoinvent impacts for the EV. By contrast, ambitious mitigation scenarios that have larger shares of technologies emitting less GHG show large reductions of these impacts, particularly in the long-term. For impacts such as metal depletion, almost no effect of the scenario is observed for the EV and the ICEV. This is mostly related to the fact that sectors that might contribute more to this impact, such as the raw materials production sector, were kept the same. For impacts like particulate matter formation, ambitious mitigation scenarios showed that EV would lead to improvements while for non-ambitious scenarios, such as the baseline scenario, the ICEV would be preferred. Exploring future pathways and related impacts, rather than predicting them as shown in chapter 4, can help outline and better inform directions for action in product-design and policy-making.

Finally, in chapter 5 a critical review of methods to interpret uncertainty analysis results was conducted. The implications of using these methods for interpretation of comparative LCA results was investigated, under the light of the goal and scope of the LCA study.

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? (Answered in chapter 5)

Comparative LCAs may support a comparative assertion regarding the relative environmental performance of one product with respect to other functionally equivalent alternatives (ISO 2006). We identified two types of goals for comparative LCAs, exploratory and confirmatory. Comparative LCAs with exploratory purposes are interested in facilitating the decision-making process by identifying differences and trade-offs in impacts between alternatives and by pointing to places in the life cycle where data refinement could benefit the assessment. For these LCAs exploratory methods to interpret uncertainty analysis results are recommended. Particularly, discernibility analysis is recommended as relative uncertainties are accounted for by this method if dependent sampling is used, while observing that trade-offs will not account for the magnitude of the difference. Comparative LCAs with confirmatory purposes are interested in evaluating hypotheses and in identifying if environmental differences are deemed statistically significant. For these LCAs confirmatory methods should be used. Particularly, modified NHST provides a better interpretation of the statistical significance of the difference in impacts between the alternatives considered. This is because this method accounts for relative uncertainties if dependent sampling is used as well as it accounts for the magnitude of the difference per impact, as part of the statistical test it is based on.

While it was evident from our critical review that for confirmatory purposes the modified NHST was the preferred method, for explorative purposes no method stood clearly out as each one had its benefits and limitations. The impact category relevance and the overlap area methods allow for the exploration of trade-offs between alternatives and account for the magnitude of the difference per impact. However, their calculation setup disregards relative uncertainties. Discernibility, which we identified as belonging to both exploratory and confirmatory types of methods, accounts for relative uncertainties but disregards the magnitude of the difference of the impacts between alternatives. Because we considered accounting for relative uncertainties more crucial in a comparative context (as shown in chapter 3 of this thesis) we suggested the use of discernibility as the preferred explorative method, with the caveat that it needs improvement to account for the magnitude of the difference of impacts between alternatives.

6.3 Further reflections

6.3.1 General implications for LCA

Acknowledging and dealing with different sources of uncertainty has implications for all phases of LCA and vice versa. Regarding the goal and scope, the goal of the LCA determines to a large extent the sources of uncertainty, which may play a crucial role in the assessment. Single-alternative LCA, comparative LCA or prospective LCA can intrinsically be affected by different sources of uncertainty given their different natures. For example, epistemological uncertainty is more important for prospective LCAs than it is for an assessment in the present, and the choice of allocation can be more important in a comparative LCA with several multifunctional processes on the foreground than it is for a single alternative LCA without multifunctional processes on the foreground. A clear notion of the goal and scope can be a good departure point for practitioners to determine which sources of uncertainty they should be addressing.

Further, some sources of uncertainty such as parameter uncertainty and methodological choices prevail in phases such as the inventory and life cycle impact assessment phases of LCA, independently of the type of assessment. Dealing with these requires specific methods applicable to LCA in a broader sense and preferably pertinent to all LCA calculation platforms to facilitate their adoption by the community. This thesis contributed to this topic and provided methods applicable to different platforms (e.g. pseudo-statistical approach) as well as supporting information that practitioners can further adopt in their assessments (e.g. prospective LCA implementation of IMAGE scenarios code in python and implementation of uncertainty-statistic methods in excel).

We showed that dealing with parameter uncertainty and uncertainty due to methodological choices can have further implications for the experimental setup used in the calculation of the LCA results. Particularly for comparative LCAs, where relative uncertainties are of outmost importance, independent sampling should not be used for comparative LCA as more recently also acknowledged by Lesage et al. (2018). These findings may be of particular importance for LCA guidelines for policy applications, such as the Product Environmental Footprint (PEF) from the European Commission. We dedicate a word to this particular aspect here.

According to the European Commission, the PEF project aimed to develop a harmonized environmental footprinting methodology that can accommodate a broader suite of relevant environmental performance criteria and to assess environmental impacts of product, through their life-cycle, in order to support the assessment and labelling of products (European Commision 2016). For this purpose, ongoing pilots in different sectors were stablished to test and develop further the product environmental footprints category rules (PEFCR). PEFCRs, still under development, mostly consist of deterministic LCAs that follow the legal approach, i.e. standardization of much of the methodological choices and data that are pre-defined in order to reduce uncertainty and increase comparability among studies of similar products in one sector. This thesis showed that embracing uncertainty, where quantifiable (as we also recognized that not all sources of uncertainty can be quantified), could be an alternative way to increase comparability of the environmental impacts between products. It provides additional information about the outcomes benefiting decision-making and it supports a statistic approach to compare similar products. For instance, the impacts of a product including many sources of uncertainty, could belong to the x% of worse, average or better performing products in a category for a specific impact. Despite that we do not develop further ideas on how to adopt some of the methods developed in this thesis in a context such as that of the PEFCR, some concrete ideas based on this thesis to progress PEFCRs towards an approach acknowledging the comparative character of uncertainty analysis, may include: using as a technique to treat choice-related uncertainties, a stochastic approach capturing many possible combinations instead of a specific-standardized choice with sensitivity scenarios (Chapter 2-3); using inventory data with underlying dependent sampling (see Lesage et al., 2018 for implications for aggregated datasets, Chapter 3); and possibly using information of the likelihood of the results to help communicate the preferred product choice (Chapter 5).

Finally, although other sources of uncertainty like ignorance and indeterminacies were not explicitly treated in this thesis, we believe they can gain particular relevance in the interpretation phase, not to say they do not appear in other phases, as they underlie the construction of scientific knowledge in general (Wynne 1992). The knowledge gained from an LCA may result in the emergence of additional uncertainties once it is used to support commitments, decision and policy making. For instance, using uncertainty analysis results to inform consumers may not necessarily be used in the expected way by consumers and quantifying such uncertainty could possibly be very difficult if possible at all. In other words, knowledge from an LCA may or may not result in additional uncertainties if expected to be valid under different social interpretations and different situations under which it was developed. Although, there is simply no way to know whether the knowledge from an LCA will influence decisions and choices leading to a sustainable future this thesis showed that the knowledge gained from acknowledging uncertainty where possible, can provide valuable and additional information about the LCA result, increasing the chances that decision and choices are indeed in the right direction. Chapter 5 showed that dealing with epistemological uncertainty enters a nonstationary, complex domain based on human behavior (Plevin 2016) which makes it difficult to predict environmental impacts, reason why the approach of this chapter is rather explorative than predictive.

6.3.2 The need to increasing replicability, transparency and robustness of LCA

There is a growing need for deepening the uncertainty dimension of LCA to increase transparency and robustness of LCA. This pressing need calls for the LCA community to further develop the science of LCA to address new societal questions and deal with issues that remain unsolved obstacles. For example, prospective LCA is one of the most prominent sub-disciplines in which a shared foundation in terms of methods, data, best practice and software solutions are lacking (Vandepaer and Gibon 2018). The UNEP-SETAC Life Cycle Initiative's Flagship Activity on Data, Methods, and Product Sustainability Information is an initiative aiming to bring technical advances to LCA and improve replicability of LCA results (Kuczenski et al. 2018). This community and initiative have declared that better model documentation is fundamental in increasing transparency and robustness in LCA. Despite of the efforts undertaken, the LCA community has still to become increasingly aware of the benefits of uncertainty analysis. This thesis showed that transparency and robustness come when explicitly acknowledging, in the case of this thesis by quantifying as much as possible, the levels of unknowns. This thesis also made an effort to provide supporting material for practitioners to further replicate the methods and case results of this thesis. Yet, acknowledging and dealing with other sources of uncertainty in LCA (where possible), for instance sources of actual ignorance and indeterminacies, has still to be pursued and simply more broadly recognized. Issues like the uncertainty of the uncertainty estimations used in this thesis e.g. the use of data quality indicators, or the applicability of these methods to different situations from the ones used in this thesis (e.g. new product-systems and new uses of the LCA results), deserve future attention.

Nowadays, uncertainty analysis is still a sub-discipline within LCA. However, uncertainty analysis has the capacity to account for many issues (e.g. data quality, allocation choice, unknown future) that diminish the scientific quality of the more widely applied deterministic point-value LCA practice. The future of LCA is in incorporating, as part of its standard practice, reproducible and transparent methods to increase the robustness of results and to explicitly acknowledge as much as possible, sources of unknowns. Although this inclusion might come at the price of more complex models, higher demands for data and data quality indicators, as well as bigger datasets, the efforts can be profitable and may even change deterministic conclusions. This thesis showed some concrete examples of ways towards more reproducible and transparent LCAs with more robust results while keeping the balance between model complexity and data demands. Documentation and relying in the probabilistic language were two fundamental aspects in achieving such a purpose and in preserving transparency.

6.4 Recommendations for future research

This thesis aimed at deepening the uncertainty dimension of environmental LCA. We addressed four questions around how to deal with three specific sources of uncertainty in different LCA applications. Yet, some issues remain to be further developed. Below, we summarize our main further research recommendations in relation to each of the chapters that addressed one research question each.

Chapter 2 and 3. On addressing choice-related and parameter uncertainty in different LCA contexts, extending and exploring other applications of the pseudo-statistical method is recommended. This and other recommendations in relation to chapter 2 and 3 are:

- Exploring the application of the pseudo-statistical method to higher level of choices for solving multi-functionality e.g. using substitution and system expansion as possible choices.
- Expanding the application of the pseudo-statistical method to propagate other discrete methodological choices in LCA e.g. different characterization methods for the same impact category.
- Applying a global sensitivity analysis to results of the pseudo-statistical method to understand how allocation choice and parameter uncertainty contribute to the total uncertainty and gain better understanding of the influence of sources of unknowns in the outcomes.
- Expanding the pseudo-statistical method to multi-functional processes in the background.
- Develop methods to map and determine which allocation methods and their methodological preference should be used in the pseudo-statistical protocol. For instance, participatory approaches actively accounting for different views by involved scientists, experts and stakeholders and patterns from meta-analysis of existing case studies.
- Standardizing the semantics around uncertainty and sensitivity analysis in LCA to facilitate the dissemination of novel methods in the two domains. Some methods like the one presented in Chapter 2, do not entirely fall in one or another type of analysis which made it difficult to communicate what it entailed.

Chapter 4. On addressing epistemological uncertainty in prospective LCA, to further improve the linkages between the ecoinvent database and IAM output is recommended. This and other recommendations in relation to chapter 4 are:

- Further data mining of the IMAGE scenarios to include as much as possible improvements of efficiency of renewable technologies and other emissions e.g. from electricity transmission.
- Expanding the use of IMAGE scenarios for prospective LCA to other economic sectors beyond the electricity sector e.g. steel, transport, agriculture, etc.
- Apply the prospective LCA approach using IMAGE scenarios to other case studies and combine it with foreground related sources of uncertainty e.g. parameter and choice uncertainty

- To improve further the inventories for relevant future technologies in line with the scenarios, such as carbon capture and storage (CCS) and concentrated solar power (CSP), and to account for their parameter uncertainty.

Chapter 5. On the interpretation of LCA results with uncertainty estimates, we recommend to further understand new issues arising from the critical review of interpretation methods as well as with incorporating this knowledge into assessing several impacts. This and other recommendations in relation to chapter 5 are:

- Investigate the effects of different techniques to quantify and propagate uncertainty on the interpretation of uncertainty analysis results in comparative LCA.
- To expand and test the discernibility method to include the magnitude of the impacts as well as the overlap area and the impact category relevance methods, to include relative uncertainties.
- Provide practical guidance to establish thresholds for acceptable uncertainty levels for different LCA applications.
- Develop understanding of the implications of acknowledging uncertainty for decision-making and communication of results to broader audiences e.g. consumers particularly in the context of product claims and consumer choices.
- Develop further understanding of the implications of dependent sampling for calculations of standardized Product Environmental Footprints (PEF) and Product Environmental Footprint Category Rules (PEFCR).