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

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Title: Deepening the uncertainty dimension of environmental Life Cycle Assessment: addressing choice, future and interpretation uncertainties.
Issue Date: 2018-10-09

Summary

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. The choice for an allocation method can have a large influence on the outcomes of LCA. Therefore, addressing the sensitivities related to the choice becomes important. Regarding time, some LCAs aim to be relevant for future decisions, which means that relevant parameters for the LCA might change in ways that are fundamentally unknown to us. Addressing epistemological uncertainties becomes crucial. Finally, selecting a method to interpret LCA results with uncertainty estimates affects the interpretation of results as different methods might lead to different conclusions. Thus, addressing uncertainty introduced due to the choice of interpretation method is also important.

It is widely-agreed that correctly dealing with these different sources of uncertainty is a vital step towards increasing the usefulness and reliability of LCA results. Practical ways to deal with uncertainty are needed. Most recent efforts have been in the direction of recognizing and increasing the community's understanding of the different sources of uncertainty as well as of their implications for different LCA applications. The aim of this thesis is to deepen the understanding of the uncertainty dimension of current LCA. By means of addressing different sources of uncertainty not yet addressed, with new methods, a clearer picture of the implications of different sources of uncertainty in LCA is provided. Although this thesis departed from broad domains of uncertainty including risk, uncertainty as conventionally described, ignorance and indeterminacies, the selected sources of uncertainty were narrowed down to the domains of risk and conventional uncertainty i.e. those due to incomplete scientific knowledge and that are to some extent quantifiable. We emphasize that this does not mean that all can be known or quantified and we make visible that ignorance and indeterminacies exist.

The issues addressed in this thesis and their related sources of uncertainty in LCA are:
1) allocation method choice in combination with parameter uncertainty,
2) accounting for future socio-technical changes in prospective LCA (epistemological uncertainty) and
3) choice of the interpretation method of uncertainty analysis results.

Each of these topics introduces uncertainty in the LCA results and to treat them this thesis uses different approaches, already existent in literature: the statistical, the scientific and the legal approaches. Within each approach, new methods are proposed

and developed such that these sources of uncertainty in LCA could be accounted for and explicitly acknowledged in the LCA results. This thesis consists of one introductory chapter (Chapter 1), four content chapters (Chapter 2 to 5) each treating one of the sources of uncertainty for a specific LCA application, and one overall discussion chapter (Chapter 6).

Research questions

On the basis of the identified sources of uncertainty and the knowledge gaps identified for each of them, the following research questions were addressed 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? (Chapter 2)

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? (Chapter 3)

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

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? (Chapter 5)

Answers to research questions

How can parameter uncertainty and uncertainty due to methodological choices be addressed? (RQ1, Chapter 2)

One way to treat parameter uncertainty and methodological choice uncertainty due to the choice of allocation methods is by means of the pseudo-statistical method proposed in chapter 2. This approach is based on Monte Carlo simulations for uncertainty propagation of quantified parameter uncertainties and of methodological preferences of allocation methods for solving multi-functional unit processes. This method enables accounting for the sensitivities of the choice of allocation method simultaneously with parameter uncertainty covering many possible combinations of these two and explicitly showing the results of such combinations without the need for one at the time scenarios. The application of this approach to a case study of a single alternative LCA showed that stochastically accounting for parameter uncertainty and for the choice of allocation

methods leads to a wider range of results. These results, better cover the full uncertainty range but only further increase absolute uncertainties in single alternative LCA results. The illustrative case study showed that for scenarios varying one at the time the allocation method the climate change impacts vary from 1.5 to 2.3, from 1 to 1.5, from 1.2 to 1.9 and from 2 to 3 kg CO_{2eq} per kg of rapeseed oil, respectively per scenario. Results for the pseudo-statistical method proposed in this chapter range from 1 to 3 kg CO_{2eq} per kg of rapeseed oil with peaks of frequency of outcomes around the medians of the one at the time allocation scenarios. The range of results of the one at the time scenarios is fully covered by the proposed method, but as mentioned this only further increases absolute uncertainties which is not per se more useful. This approach appears to be more powerful in a comparative LCA context where relative uncertainties play a role. By extending it with a global sensitivity analysis, the contribution of uncertainty due to the choice of allocation method and of parameter uncertainty to the total uncertainty of the outcomes can be determined.

What are the implications of addressing parameter uncertainty and uncertainty due to methodological choices in a comparative LCA context? (RQ2, Chapter 3)

Applying the pseudo-statistical method to propagate parameter 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 under comparison, applying paired sampling of all parameters under consideration, is the most suitable experimental setup for uncertainty analysis in comparative LCA. Failing to use such setup will not enable a sensible comparison reflecting 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 comparison of two aquaculture technologies to produce finfish showed that while deterministic LCA results can portrait one alternative as "better performing" for all impacts studied, no significant differences were observed when accounting for relative parameter and choice uncertainties with a pseudo-statistical approach. Deterministic results do not provide information on the likelihood of the outcome which portraits integrated production of fish as superior. The pseudo-statistic method results showed that monoculture production of fish leads to very similar environmental impacts as integrated multi-trophic production of the same fish, but the latter includes an additional production of oysters that could expand the economic base of the fish farm. Thus, a marginally bigger produce can be made with very similar environmental impacts. Having such information gave a more realistic assessment of the impact caused by the change in productive technology in this specific fish farm.

How can epistemological uncertainty for prospective LCA be systematically and consistently addressed? (RQ3, Chapter 4)

Scenario development in LCA is the most broadly used tool to deal with epistemological uncertainty in prospective LCA. However, to develop scenarios in LCA, it is really hard to replace all input data consistently across the LCA study in order to account for changes according to the scenarios. This is even more so, because a consistent method would not only require replacement of the foreground assumptions (i.e. parameters related directly to the activity looked at) but also all background assumptions (i.e. parameters related with supply chains of the activity looked at). For instance, in the case study discussed in Chapter 4, we discuss the choice between combustion versus electric engine vehicles. Here, not only consistent assumptions need to be made on the future performance of these vehicles, but also how changes in the future electricity mix (e.g. more renewables) would change all input parameters in the LCA. For this, we propose to link coherent integrated assessment model scenarios (a set of varied plausible futures) with background inventory data (i.e. LCI databases) to make scenario development in LCA more systematic and consistent. Because the future is unknown, one is confronted with epistemological uncertainty. To acknowledge epistemological uncertainty, we use several integrated assessment model scenarios covering different storylines that address the fact that we don't know how the future will unfold. Such approach leads to more robust results that account for varied socio-technical future paths of development and that serve to explore environmental impacts of products in the future. We showed how combustion and electric vehicles' impacts depend on the scenario and year. For some impacts, there appears to be a clearer difference in the future performance of the two vehicles, e.g. for human toxicity the scenario makes no difference as EV always performs worse. For other impacts, e.g. particulate matter formation and climate change, it is harder to distinguish which technology will perform better in the future.

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? (RQ4, Chapter 5)

After quantifying different sources of uncertainty and propagating them to LCA results the last phase is the interpretation of the uncertainty analysis outcomes. Methods to interpret LCA uncertainty analysis results can 1) help in identifying differences and trade-offs in environmental impacts between alternatives and point to places where data refinement could benefit the assessment (exploratory methods) and 2) establish statistical significance of the difference (confirmatory methods). Depending on the goal and scope of the LCA, exploratory or confirmatory methods should be used. The two most important features of interpretation methods include: 1) accounting for common uncertainties and 2) accounting for the magnitude of the difference per impact. In chapter 5 we reviewed five interpretation methods and illustrated with a case on combustion, hybrid and electric vehicles that disregarding relative uncertainties leads

to incorrect recommendations. Therefore, we considered this feature as a crucial one to be accounted for in interpretation methods. Also, we provided guidance on which method to choose according to the goal and scope of the LCA. It became evident that for exploratory purposes, no method is sufficiently developed yet as they do not cover both key features. For confirmatory purposes, one method was superior and helps establish statistical significance of the difference in environmental performance of two alternatives compared.

Main conclusions

This thesis contributed in deepening the understanding of uncertainty analysis in LCA. Three approaches to deal with uncertainty sources were used: the statistical, the scientific and the legal approaches. Each one leads to the development of guidance or a method useful to deal with different sources of uncertainty for different LCA applications. Overall, one of the most important conclusions of this thesis is that explicitly acknowledging different uncertainty sources in LCA results can provide additional information of important value. For instance, the likelihood of the results becomes known by explicitly dealing with uncertainty in comparison to deterministic LCA where the likelihood of the outcome is not known and it is usually associated with an average. Such information is important to understand the robustness of the results and thus can be valuable in decision and policy-making. Moreover, in a rapidly changing world with more unknowns than knowns and where a transition towards sustainable technologies, products and systems has never been so urgent, this information and the capability to deal with different sources of uncertainty in LCA are of outmost importance to generate reliable assessments.

Outlook

Much has yet to be done and this thesis is another step toward increasing the capacity of the LCA community to deal with uncertainty. A detailed future research agenda derived from this thesis was outlined in section 6.4. In general, any efforts in the direction of better understanding how to deal with different sources of uncertainty, their implications for different LCA types and different applications, can contribute to enlarge the knowledge and the available toolbox for LCA practitioners. An important gap yet to be filled is the ability of the LCA community to communicate in transparent and accessible ways results of uncertainty analysis to society and relevant stakeholders. Unfortunately, the value of uncertainty analysis in LCA is not so recognized perhaps because it has been depicted as a complex type of analysis which might not yield valuable information. As shown in this thesis, to answer questions regarding the environmental sustainability of product-systems, in the present and in the future, requires more than ever embracing and recognizing as much as possible, what is unknown.