Commentaries

How LCA Studies Deal with Uncertainty

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Abstract. In recent years many workers have examined the implications of various sources of uncertainty for the reliability of Life Cycle Assessment (LCA). Indeed, the International Standardization Organization (ISO) has recognised the relevance of this work by including several cautionary statements in the ISO 14040 series of standards. However, in practice, there is a risk that the significance of these uncertainties for the results of an LCA could be overlooked as practitioners strive to complete studies on time and within budget. This paper presents the findings of a survey of LCA studies we made to determine the extent to which the problem of uncertainty had been dealt with in practice. This survey revealed that the significance of the limitations on the reliability of LCA results given in the standards has not been fully appreciated by practitioners. We conclude that the standards need to be revised to ensure that LCA studies include at least a qualitative discussion on all relevant aspects of uncertainty.

Keywords: Data aggregation; data quality; impact assessment; incomplete data; ISO 14040; life cycle assessment; methodology; potential impacts; uncertainty

Introduction

Many of the concerns that have been expressed about the accuracy of LCA results are linked to potentially significant sources of uncertainty [1–2]. Some of these uncertainties are common to all environmental assessment techniques [3–4]. They include poor data quality, invalid or non-transparent assumptions and failure to perform sensitivity analyses [4–9].

In recent years there has been much discussion about how the data collected during the inventory phase of an LCA relates to actual environmental impacts [10–11]. The crux of the problem lies with the simplified forms of data collection in LCA. Though the inventory quantifies inputs of energy and materials and releases of wastes on a system-wide basis, it lacks the spatial, temporal, dose-response and threshold information that would be needed for site-specific assessment [12]. The standard permits this data to be omitted from the inventory because otherwise the vast quantity of data that would need to be collected would render the technique impractical [13–15]. However, Owens [11,16] argues that without such data significant sources of uncertainty are introduced to the impact assessment phase of the LCA, and that the magnitude of these uncertainties will vary depending on the effect. Therefore, the impact predicted by life-cycle impact assessment (LCIA) may not accord with the actual impact [17–21].

Much of the confusion concerning the relevance of LCIA results is linked to the use of aggregated data during the impact assessment phase. Indeed, White et al. make the point that the practice of calculating global parameters for impact categories by aggregating data across the life cycle assumes a worst-case scenario that could "misguide improvement measures or policy-making" [13]. Though these category indicators can provide simplified directional perspective on environmental topics, they are not a measurement of actual effects [11]. The Society of Environmental Toxicology And Chemistry (SETAC) and the International Standardization Organization (ISO) now clearly state that, unlike traditional forms of environmental impact assessment, LCA is not measuring or predicting actual effects, predicting potential effects, or estimating risks [22–26]. Though the significance of these limitations has been debated widely in the literature, it is not clear to what extent this discussion has influenced LCA studies in practice. Therefore, the aim of this paper is to investigate how practitioners have dealt with the problem of uncertainty in their studies.

To achieve this aim we begin with a brief examination of the ISO standards to establish how they deal with these sources of uncertainty. We then undertake an analysis of journal articles, reports and summaries featuring the results of various LCA studies to see how the problem of uncertainty is handled in practice. We conclude with recommendations that emerge from a comparison of the standards and the findings of our analysis.

1 ISO Standards

To improve the accuracy of LCA results, ISO has documented the need for a transparent and peer-reviewed process. Indeed, a large part of the *Life Cycle Interpretation* standard is devoted to examining the reliability of the work undertaken in the earlier phases of the LCA [27]. Thus, it is not surprising to find that the problem of uncertainty is emphasized throughout the standards. For example, the *Life Cycle Interpretation* standard alerts users of the methodology to several potential sources of uncertainty:

> The objective of the sensitivity check is to assess the reliability of the final results and conclusions by determining whether they are affected by uncertainties in the data, allocation methods or calculation of category indicator results, etc. This assessment shall include the results of the sensitivity analysis and uncertainty analysis, if [emphasis added] performed in the preceding phases (LCI, LCIA), and may indicate the need for further sensitivity analysis [27].

However, as this section shows, even though the standards encourage practitioners to undertake uncertainty analysis, this is not a mandatory requirement. Examining the other standards provides further insights into the ISO perspective on uncertainty. In *Goal and scope definition and inventory analysis* uncertainty is directly linked to data quality:

> In addition, uncertainty is introduced into the results of an LCI due to cumulative effects of input uncertainties and data variability. Uncertainty analysis as applied to LCI is a technique in its infancy. Nevertheless it would help to characterize uncertainty in results using ranges and/or probability distributions to determine uncertainty in LCI results and conclusions. Whenever feasible, such analysis should be performed to better explain and support the LCI conclusions [12].

The standard not only alerts the assessor to this potential source of uncertainty but also suggests an appropriate course of action. However, the emphasis in the standards is on quantitative rather then qualitative uncertainty analysis [24]. The quantitative analysis of uncertainties arising from the influence of data quality on LCA results is still very much in its infancy [28], and practitioners could be forgiven for excluding such an analysis from their studies. In practice, the extra time and cost involved in quantifying data uncertainty is also a deterrent to undertaking such an analysis [9]. Nevertheless, it can be argued that even where quantification is not attempted, a qualitative assessment of the reliability of the data should accompany the results of the inventory [9, 28].

Perhaps the most problematic source of uncertainty is the lack of site-specific information collected during the inventory phase [1, 14]. Indeed, ISO has recognized this problem, and these data limitations are highlighted early in the introduction of *Principles and framework*:

> The lack of spatial and temporal dimensions in the inventory data used for impact assessment introduces uncertainty in impact results. This uncertainty varies with the spatial and temporal characteristics of each impact category [23].

And again in *Life Cycle Impact Assessment*:

> LCIA typically excludes spatial, temporal, threshold and dose response information and combines emissions or activities over space and/or time. This may diminish the environmental relevance of the indicator result [24].

These statements recognise that important data is missing from the inventory, thus potentially undermining the impact results. However, the standards do not elaborate further on this point other than acknowledging that there is a link between uncertainty and the spatial and temporal attributes of an environmental effect.

Two important conclusions arise from the preceding discussion. First, the standards are explicit about the existence of a range of uncertainties that have the potential to undermine the results of an LCA. Therefore, users of this methodology should at least be aware of these uncertainties and be able to discuss their importance in the context of their study. Second, though the standards clearly support the use of quantitative approaches for uncertainty analysis, they appear to overlook the potentially useful contribution of a qualitative approach.

Even though a qualitative assessment lacks the numerical precision of a quantitative analysis, it is still able to explain how and why these uncertainties are important when interpreting the results of an LCA. Although at this stage in the evolution of LCA methods, quantifying the uncertainty introduced by the exclusion of spatial, temporal, dose-response and threshold data from the inventory is unrealistic, a qualitative analysis of this source of uncertainty is valuable because it can be used to explain the relevance of indicator results for policy-development and decision-making.

2 Review of LCA Studies

2.1 Research hypothesis

Two sources of uncertainty, in particular, receive special attention in the standards because of their ability to significantly compromise the reliability of LCA results. They are poor data quality and the exclusion of site-specific data from the inventory. Whereas quality is a practical problem encountered during the inventory phase of an LCA, the lack of site-specific data is a constraint of the methodology itself. Though these problems also affect other environmental assessment techniques, the size and complexity of the data collection and manipulation tasks prescribed in the LCA methodology means that practitioners will always need to address these limitations in their studies.

We recognize that although the implications of these sources of uncertainty for LCA results have been discussed widely in the literature, as yet only limited progress has been made towards their resolution [1–11, 13–21]. Nevertheless, we might hypothesize that, before they draw any concrete conclusions about the potential impacts of a product system, LCA practitioners would include, as part of their discussion, a cautionary statement explaining the sources of uncertainty for each impact category under examination. This would presumably result in appropriate caveats being applied to their impact results and recommendations for a more detailed quantitative assessment of some impact categories (one that would move beyond the constraints imposed by the LCI). To test this hypothesis, we looked for evidence in journal articles and reports that would indicate awareness of these uncertainties and, further, gave guidance on how to interpret the study results.

2.2 Research approach

LCA studies were acquired from a variety of sources, and included detailed reports, report summaries and case study articles. Our strategy was to initially review each study in general terms to determine whether or not discussions of uncertainty figured prominently in the presentation of the results. Where uncertainty was mentioned in a study, we then reviewed it in detail to establish whether the practitioner recognized the importance of possible uncertainty and dealt with it in discussing the results of the study. The following criteria were used to select the studies for analysis from those that were readily available:

- We included only those studies that performed the inventory and impact assessment steps as described in the standard LCA methodology. As we noted earlier, significant uncertainties are present when practitioners use aggregated life cycle inventory data as indicators of environmental impact.
- We selected studies that assessed a mix of environmental burdens, including global warming, ozone depletion, acidification, eutrophication, photochemical oxidants, ecotoxicological and human health effects.
- We included only studies that were published post-1997. By this time these uncertainties had been discussed widely in the literature [10–11, 13–14, 16–20] and the limitations were also documented in the framework standard, ISO 14040 [23].

This left us with 30 LCA studies to review (see Appendix). Each study was then examined using the following set of questions:

- Did the LCA claim to use ISO methodology or not? The ISO standards have included several statements on the problem of uncertainty. Other versions of the methodology are less explicit about these limitations.
- Was the document a report or refereed article? Many of the studies were from refereed journals. We might expect that the extra scrutiny by reviewers would result in more discussion on uncertainty in these articles.
- Was an uncertainty analysis (qualitative or quantitative) performed on any part of the study? This was the key question as far as our hypothesis was concerned.
- Was inventory data quality discussed? In our review data quality was interpreted in the broadest sense. Indicators of data quality may include accuracy, bias, reproducibility, completeness and a whole set of other indicators [28]. However, the aim of our review was not to analyse the use of one or all of these indicators. Rather, we used their presence to indicate that data quality had been addressed. Poor data quality contributes to uncertainty and is a recurring problem in LCA studies.
- Was the lack of site-specific inventory data discussed? The deliberate exclusion of site-specific data from the inventory introduces additional sources of uncertainty into LCA results. Even if this problem is not raised explicitly, some studies may have expressed concern over this deficiency in the impact assessment phase of the study. Studies where the lack of site-specific data is noted indicate an awareness of this constraint.
- Did the study express reservations about the relevance of indicator results derived from data aggregated across the life cycle? The uncertainty in impact assessment is greatest for effects that are typically local and of short duration (e.g. ecotoxicological and human health effects) [11,14,16].
- Was there evidence of a distinction between potential and actual impacts? We felt that this point could also be used as a proxy for uncertainty as it indicates a degree of understanding of the limitations inherent to LCA.

3 Results and Discussion

The results of our analysis are presented in two parts. The first part is a review of all 30 of the studies in the sample to ascertain whether practitioners reported uncertainty in their results, either explicitly or by implication, while discussing some of the problems noted earlier in this paper. The second part of the review examines, in greater detail, the 14 studies in which uncertainty was reported, to determine the nature of these deliberations.

We began our review of the 30 studies with two simple objectives. The first was to identify those studies that reported uncertainty, and the second was to investigate whether a quantitative or qualitative uncertainty analysis had been performed. Because this initial examination of the studies was intended to be nothing more than a superficial review, we were prepared to accept almost any evidence that indicated awareness of sources of uncertainty. For example, any study that mentioned the word uncertainty or discussed limitations that contributed to increased uncertainty in impact assessment results were deemed to have reported the problem. Similarly, we considered the presentation of any quantitative data measuring uncertainty thresholds to be sufficient evidence of a quantitative analysis and a discussion of the implications for impact assessment of these uncertainties to be sufficient evidence of a qualitative analysis. The results of the preliminary review of studies are given in **Table 1**.

Table 1: The extent to which the sample of LCA studies reported problems of uncertainty

Document type	Number reviewed	LCA methodology		Uncertainty reported		Quantitative analysis		Qualitative analysis	
		ISO	Non-ISO	Yes	No	Yes	No	Yes	No
Report	6 = 20%	4	2	1(E) + 3(I) = 4	2	0	6	1	5
Article	24 = 80%	15	9	3(E) + 7(I) = 10	14	1	23	1	23
Reports & Articles	30 = 100%	63%	37%	47%	53%	3%	97%	7%	93%

Yes: Evidence that this aspect has had been considered
No: Not included in the study
E: Uncertainty reported explicitly
I: Uncertainty reported by implication (i.e. data quality, lack of site-specific inventory data, inadequate impact assessment methods or potential vs. actual effects)

Table 2: The problems dealt with in the LCA studies that reported uncertainty

Document type	Number reporting uncertainty	LCA methodology		Problems with data quality		Lack of site-specific data		Data aggregation		Potential vs. actual impacts	
		ISO	Non-ISO	Yes	No	Yes	No	Yes	No	Yes	No
Report	4 = 29%	2	2	4	0	1	3	2	2	3	1
Article	10 = 71%	8	2	10	0	0	10	2	8	4	6
Reports & Articles	14 = 100%	71%	29%	100%	0%	3%	97%	13%	87%	50%	50%

Yes: Problem was dealt with to some extent in the study
No: Problem was not discussed in the study

The most significant result from Table 1 is evidence that very few LCA studies perform even a qualitative analysis of the uncertainties linked to impact assessment. The one study in our review that combined an in-depth discussion of uncertainty with a quantitative analysis did so for matters related to data quality only, and did not explore other sources of uncertainty such as the implications for impact assessment of excluding site-specific data from the inventory. In fact, more than half of the studies (53%) made no reference to problems commonly associated with uncertainty. This is surprising when we consider that 63% of the studies purported to comply with the ISO methodology, which is explicit about a range of uncertainties that have the potential to undermine the results of an LCA. Of the fourteen (47%) studies that did refer to these problems, only four of these made an explicit connection with uncertainty (labelled with an E in Table 1).

In the second part of out study we performed a more detailed review of the 14 studies that were deemed to have reported the problem of uncertainty. We were interested in understanding whether practitioners had explained the implications of these uncertainties for the reliability of impact assessment results. We also wanted to investigate whether particular sources of uncertainty were better understood and therefore acknowledged more often than others.

The results of the detailed review of these 14 studies are given in **Table 2**.

Of the studies in the sample that discussed problems linked to uncertainty, data quality was by far the most commonly reported concern. This is not surprising, as good data quality is an important objective for all environmental assessment techniques. However, other than emphasising the importance of using rigorous data collection methods, none of the authors drew specific conclusions about how these data quality problems affected the reliability of their LCA results.

Though there was widespread recognition of the importance of data quality, this was not the case for sources of uncertainty specific to LCA. For example, only one of the studies raised the problem of site-specific inventory data. This study overcame this deficiency by assessing 'non-local' environmental impacts. Otherwise, the significance for impact assessment results of a lack of site-specific data was overlooked. This is surprising when we consider that the majority of the studies claimed compliance with the ISO 14040 methodology, which is explicit about this data limitation. As this problem has also been discussed in some detail in the literature [10–21], practitioners should at least be able to make a qualitative assessment of how this constraint affected their results.

Very few of the studies questioned the accuracy of the impact assessment methods used and, in particular, whether it is always appropriate to aggregate data across the life cycle. Of the 13% that did, reservations were expressed only about LCA's ability to derive meaningful information on ecotoxicological and human health impacts. These arguments did not extend to cumulative effects that vary significantly across time and space (e.g. photochemical oxidants, acidification, eutrophication).

Half of the studies in this group emphasised the distinction between potential impacts and actual impacts. This distinction is important because it has implications for the relevance of impact assessment results to real world policy problems. However, this observation was usually made in passing, and was seldom explained. For example, none of the studies discussed the significance of global aggregate indicator data and why it represents a worst-case scenario for impact assessment [13]. Therefore, it would not be surprising if policy-developers or decision-makers assumed that the indicators of impact were an accurate reflection of reality. This could then lead to the imposition of unwarranted policies.

These results indicate that for many LCA practitioners the constraints on impact assessment imposed by the inventory step of LCA are largely unrecognised. This is an unexpected outcome, and is contrary to our initial hypothesis. In our opinion, steps should be taken to ensure that any study that undertakes an impact assessment based on an LCI should, at least, include a qualitative discussion of the limitations and uncertainties involved. Without it, the credibility of a study's conclusions is at risk [29] and the relevance of the technique's results will continue to be questioned [30].

4 Conclusions

It is clear that LCA results are subject to many sources of uncertainty. Some of these problems are common to all environmental assessment techniques [3] and some are peculiar to LCA. Some can be overcome by rigorously following the procedures described in the standards, while others must be tolerated because they are inherent in the current LCA approach.

Though there is an active debate within the literature on the relevance of life cycle impact assessment results, there is scant evidence that the implications of these limitations are being taken into account within LCA studies. This is particularly true for uncertainties introduced by the methodology, such as the lack of site-specific data in the inventory and the aggregation of data over different spatial and temporal scales. If practitioners of LCA continue to neglect the problem of uncertainty in their work, they run the risk of generating conclusions that cannot be justified by the indicator results.

Though LCA can effectively assess resource use and efficiency and can identify links between emissions and some environmental effects, the accuracy of these associations will vary from study to study, and this must be made transparent to policy and decision-makers. Therefore, it is imperative that studies include an explanation of the uncertainties that arise during the impact assessment phase of an LCA. Unfortunately, as our survey shows, this is not the case in practice. Even though these problems are flagged in the ISO standards, the message is failing to get through. Thus, it would appear that the significance of the stated limitations has not been fully appreciated. We believe that the standards need to be revised to ensure that LCA studies include at least a qualitative discussion on all relevant aspects of uncertainty.

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Framework for Modelling Data Uncertainty in Life Cycle Inventories

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Abstract. Modelling data uncertainty is not common practice in life cycle inventories (LCI), although different techniques are available for estimating and expressing uncertainties, and for propagating the uncertainties to the final model results. To clarify and stimulate the use of data uncertainty assessments in common LCI practice, the SETAC working group Data Availability and Quality presents a framework for data uncertainty assessment in LCI. Data uncertainty is divided in two categories: (1) lack of data, further specified as complete lack of data (data gaps) and a lack of representative data, and (2) data inaccuracy. Filling data gaps can be done by input-output modelling, using information for similar products or the main ingredients of a product, and applying the law of mass conservation. Lack of temporal, geographical and further technological correlation between the data used and needed may be accounted for by applying uncertainty factors to the non-representative data. Stochastic modelling, which can be performed by Monte Carlo simulation, is a promising technique to deal with data inaccuracy in LCIs.