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Qualitative and quantitative approaches dealing with uncertainty in life cycle assessment (LCA) of complex systems: towards a selective integration of uncertainty according to LCA objectives — Source link

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A qualitative, quantitative or mixed approach to deal with uncertainty in Life Cycle Assessment of complex systems: towards a selective integration of uncertainty according to LCA objectives

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Abstract: Since the emergence of Life Cycle Assessment (LCA), many studies have focused on the integration of uncertainties. Nevertheless, Data Quality Assessment (DQA) and statistical approaches are not yet widely used to quantify uncertainty, and when used, methodologies are neither uniform nor rigorous. Moreover, the data required to propagate and estimate the overall uncertainty are often lacking. Finally, the quantification of uncertainty could introduce more confusion in decision-making.
In this context, we propose joint implementation of both the qualitative and quantitative approaches to estimate uncertainties when performing Life Cycle Assessment of complex systems. Using an existing LCA on grocery bags, this study first attempts to demonstrate the usefulness of both the qualitative and quantitative approaches to deal with uncertainty. Secondly, given that data collection is very time-consuming, the usefulness of both the qualitative and quantitative approaches will be discussed.

Key words: Life Cycle Assessment, Data Quality Assessment, uncertainty, quantification, propagation, methodology, Eco-design.

1 - Introduction

1.1 - Background

Life Cycle Assessment (LCA) provides a methodological framework to assess the environmental impacts of products, processes or services over their entire life cycle. LCA appeared in Europe and United States in the early 1970s. Because of the lack of standardisation and the various methodological choices made by practitioners at the time, many LCAs resulted in different and sometimes conflicting conclusions. Consequently, it was decided to harmonise the LCA procedure to avoid such problems (Russel et al. 2005). First the SETAC (Society of Environmental Toxicology and Chemistry) in 1990, followed by the International Organization for Standardisation (ISO) in 1997, respectively developed a "code of practice" (Consoli et al. 1993) and the "ISO 1404x series" (ISO 1. 2006) (ISO 2. 2006).

Although LCA is currently a well-established practice, uncertainties are not systematically assessed and included in LCA results. Moreover, uncertainties have rarely been studied, along with their impact on decision-making (Maurice et al. 2000).

1.2 - Objectives

This paper aims to discuss uncertainties relating to the LCA procedure and Life Cycle Inventory (LCI) compilation. Many methods were developed and used in the last decade to take into account the type of uncertainty. Nevertheless, it would seem that no standard procedure exists to assess data quality and quantify uncertainties. The successive implementation of both qualitative and quantitative approaches to deal with uncertainty in LCAs of complex systems is proposed. The usefulness of these approaches is then examined, and finally a selective implementation of the qualitative, quantitative or mixed approaches, depending on the purpose of the LCA, is discussed.

1.3 - Methodology

In a first phase, based on a literature survey, uncertainties are classified according to nature and then located in the LCA procedure. Then we discuss the qualitative and quantitative approaches and we assess their usefulness through several experiments based on an existing LCA. Finally, considering the advantages and limitations highlighted during these experiments and the LCA objectives, we propose and discuss a selective implementation of the qualitative, quantitative or mixed approach.

2 - Identifying of domains of uncertainty in Life Cycle Assessment

Even if LCA is performed in compliance with ISO 14040, ISO 14044 and other guidelines such as "the code of practice", final results generally suffer from uncertainties.
Although many methods were developed in the last decade, they could not be systematically applied because of the various types of uncertainty. This chapter is supported by previous publications dealing with uncertainty and available tools to deal with it.

2.1 - Domains and types of uncertainty

Defining the different types of uncertainty in order to overcome their influence is very helpful. Indeed, many tools exist to estimate or quantify uncertainty but their implementation directly depends on the nature of these uncertainties.
Several studies were already performed in last decade on identifying the type of uncertainty one may encounter when performing an LCA and the different available tools to treat them (Heijungs 1996) (Weidema, Wesnaes 1996) (Björklund 2002) (Vigon, Jensen 1995).
To summarize these works, uncertainties can be categorized according to nature and divided into three main groups:

- uncertainties related to methodological choices
- uncertainties related to the data set
- uncertainties related to the knowledge of the system under study and its environment (regulation, market)

Methodological choices are essentially linked to the orientation of the study. When modelling parameters such as boundaries, functional unit, objectives, scope and environmental impacts, categories for example must be defined.
Uncertainty relating to the system and its environment can be characterised by the practitioner's level of knowledge. Indeed, a lack of knowledge can lead to cut-off rules or model simplification introducing additional uncertainties. This type of uncertainty also covers future situations and events such as new regulations or market transformation which may directly impact production conditions or the usage phase of the product or process under study.
Finally, uncertainty concerning the dataset is essentially linked to two different aspects. On one hand, one may question the accuracy of the data included in the Life Cycle Inventory. On the other hand, uncertainty could be considered as the variability of the true value. As was previously said, in this case the type of uncertainty is different. The accuracy results from an assessment or a judgement, whereas the variability is represented by a numerical value that can be managed using statistical approaches. Considering these domains of uncertainty, several typologies have already been proposed.
Huijbregts and Norris (2001), for example, divided data uncertainty into two main groups: lack of data and data inaccuracy. Funtowitcz and Ravetz (1990) defined three main groups: data, model and completeness uncertainties. Heijungs (2004) summarised the different classifications according to several authors. Finally

Huijbregts (2003) considered three sources of uncertainty: parameter uncertainty reflecting the variability, scenario uncertainty and model uncertainty.

2.2 - Uncertainty location in the Life Cycle Assessment

Bjorklund (2002) proposed a typology of uncertainties and located them in the different steps of the LCA procedure. Two observations can be made regarding this previous research work (Table 1). First, uncertainty can simply be divided into two groups according to nature, on one hand uncertainty linked to parameters that cannot be numerically estimated, and on the other hand uncertainties linked to numerical parameters. Indeed, model choices, data representativeness, scenarios or epistemological uncertainty do not refer to numerical values but rather to knowledge and subjective judgement, while statistical distributions or variability refer to numerical values.

Type of uncertainty	Goal & scope	Life Cycle Inventory	Impact assessment
Data inaccuracy		×	×
Lack of data		×	×
Lack of representativeness		×	
Methodological choices	×	×	×
Spatial variability		×	×
Temporal variability		×	×
Object VS source variability		×	
Epistemological uncertainty	×	×	×

Table 1 : Classification and location of uncertainty in LCA from Björklund (2002)

The second observation concerns the location of the uncertainty. Indeed, each LCA step (e.g. goal & scope, inventory, choice of impact categories, classification and characterisation) has a degree of uncertainty, but only the LCI and the characterisation step contain all the identified types of uncertainty. Assuming that uncertainties located in the LCI are directly propagated and amplified throughout the procedure, the compilation of the LCI appears to be a key step to manage them.

2.3 - Aggregated vs. disaggregated data

A last source of uncertainty was identified. It deals with the use of aggregated data to perform a LCA. First, the use of aggregated data often suffers from a lack of knowledge about aggregation factor which is problematic. Indeed, information from different unit processes related to their respective data quality and uncertainty are missing and individual contribution to the overall uncertainty is often hard to determine.

Moreover, the use of aggregated LCI is not environmentally realistic. Consumptions and emissions are summed from different unit processes contributing to different life cycle steps and from different locations. It is assumed that a combination of emissions provide a global exposure factor which will never occur. Consequently the environmental impact assessment of such LCI conduces to an overestimated environmental impact.

Consequently, this paper is restricted to the LCI and its management through the use of both qualitative and quantitative approaches. The influence of level of detail and aggregation method on the overall result is excluded from this paper. This problem will be addressed in a future article.

3 - Assessing uncertainty through both qualitative and quantitative approaches

3.1 - Qualitative approach

The qualitative approach seems to be a well-established practice when dealing with LCA uncertainty even if it is not systematically implemented (Björklund 2002) (Ross, Evans, Webber 2002). Developed in the early 1990s (Funtowicz, Ravetz 1990) (Weidema, Wesnaes 1996), this approach was implemented (Vigon, Jensen 1995) and modified in several works dealing with their integration into the final LCA results (US EPA 2001) (RECORD 1998) (Fava et al. 1992) (Labouze et al. 1996). At present time, the data quality assessment is systematically implemented by the Swiss Centre for Life Cycle Inventories in the EcoInvent database (Frischknecht et al. 2005).

The qualitative approach is based on the relation highlighted by the SETAC (1992). Indeed it is assumed that the overall quality of results depends on the data quality and the quality of models. Consequently an LCI built on high quality data guaranties a good environmental impact assessment. Its implementation allows practitioner to control that the data collection match LCA objectives.

The data quality approach assesses information qualifying information (Meta data). Each data included in the LCI is assessed using a pedigree matrix and its quality is compared to the Data Quality Objectives (DQO) defined in goal and scope. The DQO reflect the quality to be ideally reached during data collection. These DQO are defined in accordance with LCA objectives and level of details to be obtained. Usually site specific data measurements are preferred. Nevertheless this type of data is often hard to obtain because of confidential purposes. To face this limitation, a lower data quality may be accepted for data with less importance.

The pedigree matrix is composed of several criteria qualifying information. Using this tool, data are rated according to a qualitative scale defined from 1 to 5, from the best representativeness to the worst, respectively (Table 2).

Criterion	**1**	**2**	**3**	**4**	**5**
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non verified data partly based on assumptions	Qualified estimate (industrial expert)	Non qualified estimate
Completeness	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from a smaller number of sites but for adequate periods	Representative data from an adequate number of sites but from shorter periods	Representative data but from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Representativeness unknown or incomplete data from a smaller number of sites and/or from shorter periods
Temporal correlation	Less than 3 years of difference with year of study	Less than 6 years difference	Less than 10 years difference	Less than 15 years difference	Age of data unknown or more than 15 years of difference
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar productions conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Technological correlation	Data from companies, processes and materials under study	Data from processes and materials under study but from different companies	Data from processes and materials under study but from different technology	Data on related processes or materials but same technology	Data on related processes or materials but different technology

Table 2 : Pedigree matrix composed of five independent criteria (Weidema & Wesnaes, 1996)

The original matrix was composed of the following 5 independent factors considered sufficient to estimate the reliability of a single data (Weidema, Wesnaes 1996):

- completeness, related to the statistical properties of the sample and the period of collection
- reliability, related to the acquisition method
- temporal correlation, defining the time difference between the study and the period the data is representative of,
- geographical correlation, estimating the difference between the area defined in the study and the area the data is representative of. This criterion takes into account not only location but also production conditions.
- technological correlation, which defines a correlation between the technology and materials under study and those the data is representative of.

Once rated, the difference between the scores for each data and the DQO is estimated to define the representativeness of the LCI. According to the DQA (Data Quality Assessment) results, three options are envisaged. In general, if the DQO are reached, the LCA can be continued. If the difference is significant, additional data collection could be planned to increase data relevancy, the decision could be taken to stop the LCA, or finally the LCA could be continued with an explanation of the lack of accuracy. Such decision does not obey to standard procedure and is strongly influenced by the final LCA objectives.
This approach seems to be well established not only with LCA practitioners but also with LCA software suppliers[1][2].

3.2 - Quantitative approach

The main alternative to treat uncertainty consists in a quantitative approach. This approach attempts to define the variability around which the true value is located. In general this type of analysis uses conventional statistics. Value variability is assessed and confidence intervals are identified. Several methods are used today. The confidence interval can be estimated through extreme values, fuzzy logic approaches are increasingly implemented, and Gaussian error propagation formulas are also used. Nevertheless, it seems that Monte Carlo simulations are still the most common practice to quantify and propagate from individual input to final results (Ciroth 2004).
The real interest is to assess the overall uncertainty concerning the final environmental impacts. Monte Carlo simulations or similar methods, such as Latin Hyper Cube simulations, are widely used to deal with uncertainty in LCA. Indeed, a recent survey of quantitative approaches to deal with uncertainty in LCA highlighted the fact that in every LCA dealing with uncertainty, parameter uncertainty was estimated. Moreover, the most common practice to quantify and propagate these uncertainties is the use of Monte Carlo simulation (Lloyd. SM., Ries. R. 2007).
These analyses integrate the range of data and the statistical distribution of each data included in the dataset to simulate the final result. When assessing the environmental impact of product and process, methods used to translate amount of substances or materials emitted or consumed into environmental load, GWP in kg CO2 equivalent for example, are based on linear function linking the amount emitted or consumed and the environmental impact factor of this substance or material for the impact category concerned. Global Warming Potential of methane (Impact factor) for example is equal to 25 (IPCC 2007). Consequently the amount of methane must be multiply by 25 to obtain its contribution to the GWP in term of CO2 eq. This type of calculus is performed for each substance or material once classified by environmental impact categories. Then all impacts contributing to a specific impact category are summed to provide the overall impact of the system. Consequently, the variability of the final result depends on the variability of the substance contribution to the impact category in term of amount emitted.
Each simulation is stored before another is performed. The final pool of simulations defines a probable final result, with its distribution and confidence interval. Each uncertainty identified in the LCI is propagated through calculation steps (Geisler et al. 2005).
When samples are smaller or when the only available data are the minimum and the maximum, the calculation of extreme values can be useful. This consists in defining lower and upper values for each parameter. Combining them makes it possible to calculate the lower and upper value of the overall area (Heijungs 1996) (Suh 2002).
The quantitative approach is increasingly used in LCA. Nevertheless, its implementation essentially suffers from the availability of sufficient samples to identify statistical parameters.

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[1] www.pre.nl/simapro.html
[2] www.umberto.fr

4 - Grocery bags LCA : towards a mixed approach to deal with uncertainty

This chapter proposes to implement first qualitative and then quantitative approaches to treat uncertainty. The case study used in this article is taken from a previous LCA published in 2004. It provides us with a good subject to experiment with in order to analyze the usefulness and limits of these two approaches.

4.1 - Case study overview

The case study proposed in this article deals with the environmental impact assessment of grocery bags. The study was ordered by Carrefour and realised by Ecobilan (2004). The main objectives were the following:

- to quantify the environmental impacts of different grocery bag alternatives over their entire life cycle,
- to acquire quantified and reliable environmental impact results in order to open discussions with economic partners such as NGOs, suppliers and consumers,
- to define an environmental strategy based on LCA results.

The life cycle taken into consideration included the extraction, transport and production of raw materials (plastics, ink, pigments and glue), grocery bag production, transport, distribution, and use, and finally its end of life.

The discussion proposed in this work paper is limited to the extraction and production of raw materials (High Density Poly Ethylene, Low Density Poly Ethylene). Initially, four alternatives were compared: an HDPE bag (single use), an LDPE bag (reusable), a paper bag (recycled paper) and a biodegradable bag. Because data relating to the last two alternatives were directly collected from the manufacturer, these data are not available in the published report. Consequently, the biodegradable and paper bags were excluded from the present study.

Moreover, the environmental impact categories initially considered were the global warming potential (GWP), acidification, eutrophication and photochemical oxidation. The presented results only include the first two categories.

4.2 - Using DQA to identify the most relevant data

Data concerning the extraction of raw materials and the production of sub-systems to produce or build the system under study are often hard to collect. This could be explained by the fact that owners are first level suppliers in the best cases, or of a lower level. Nevertheless, many databases have been built since the appearance of LCA that provide this type of data. But how does one identify the most relevant data between the different available sources?

To answer this question, the production of HDPE was taken as an example. In this experiment, five available sources were assessed using a pedigree matrix. The main objective was to determine if such a method is useful to identify the most relevant data when building the LCI. In this context a first environmental impact assessment was performed for each available dataset using the method CML Baseline 2000[3] developed by the Leiden Institute of Environmental Sciences (Guinée et al. 2002). This first assessment only considers single values, excluding uncertainty on input data. Environmental impacts are representative of the amount of raw material needed to satisfy the functional unit defined in the original study: Packaging of 9000 liters of products corresponding to the average volume purchased by a European consumer over a period of one year (Ecobilan 2004).

Figure 1 compares the environmental performances of five different HDPE production operations (from cradle-to-gate) with respect to Global Warming Potential and Acidification, respectively. Environmental impact assessment was performed using aggregated data, disaggregated unit processes being unavailable.

[3] www.leidenuniv.nl

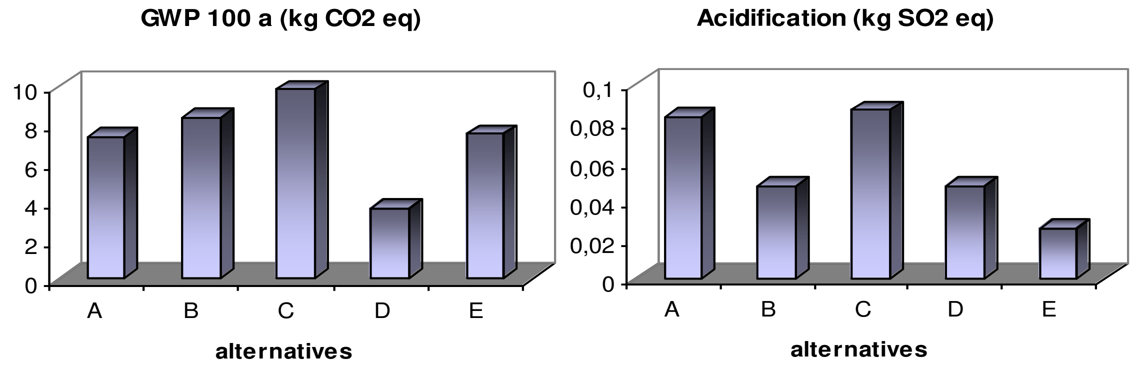

Figure 1: Environmental comparison of five types of HDPE production with respect to GWP and Acidification respectively

The HDPE production used in the original study corresponds to alternative E. Environmental impacts are slightly different from the original results even though the same sources were modelled. This could be explained by the successive updates applied to LCI databases and Eco indicators.
The results presented in Figure 1 highlight the fact that environmental impacts vary from one alternative to another and from one environmental impact category to another. For a GWP of 100 years, alternative E is more impacting than alternative D, while opposite results are obtained for Acidification.

Regarding the GWP, alternatives A, B and E have a very close score, while alternative C is the most impacting and alternative D appears to be the most environmentally friendly.
For acidification, the two pairs A-C and B-D respectively show similar environmental impacts. The friendliest environmental alternative corresponds to production E.
In view of these results, choosing between alternatives with similar impacts seems less impacting on final results than choosing between alternatives with significantly different environmental impacts.
In this context, the use of the qualitative approach appears to be helpful. Besides the fact that its implementation helps practitioners to control data quality, this method seems to be sufficiently discriminating to help choose the most accurate data.
In order to verify this assumption, a DQA was performed for each of the five alternatives. Each criterion was scored using the pedigree matrix proposed and designed by Weidema (1996), and we assumed that the DQO for the HDPE production were the following:

- measurements are preferred, but verified data based on assumptions could be used in the LCI [2]
- the data are extracted from a sample of sufficient size collected over an adequate period [1]
- the data should be representative of the situation in 2002 [1]
- the data should be representative of production conditions in Western Europe [1]
- the data required should be representative of the average technology and include data from companies [1,2]

The DQA results are summarised in Table 3.
They provide us with several additional elements of information. First, the best representativeness is attributed to alternative E. Aside from the technological correlation, every single score is equal or less than 2, which guarantees good quality. Even if all the criteria are not satisfied compared to the DQO, alternative E appears to have the most relevant data. The third criterion is the discriminating factor in this case and reinforces the fact that alternative E is the most representative (temporal correlation).
In addition, considering the other alternatives, it is possible to identify a lack of quality. Alternatives C and D for example show poor accuracy for data acquisition and temporal correlation. These data could be considered obsolete.
The use of the pedigree matrix appears useful in this case to identify the most relevant data to be included in the LCI when several sources are available. Moreover, the implementation of such an approach allows a cartography of the LCI, locating any potential lack of data and data inaccuracy even if the data gaps are consequently not rated. These results improve knowledge of the dataset and the identification of the domains the practitioner must pay attention to.

Alternative	Data Quality Assessment	Comments	Satisfied Criteria (n/5)
A	[1;2;**3**;1;3]	Time period : 92-95 Geo : Western Europe Average technology Data extracted from the survey of 10 European plants producing 1,3Mt/4Mt (92-93)	2
B	[1;2;**4**;1;3]	Time period : 92-95 Geo : Western Europe (Swiss) Average technology Survey of 10 plants	2
C	[4;2;**5**;1;3]	Time period : 85-89 Geo : Western Europe Data from Germany and Switzerland Average Technology	1
D	[4;2;**5**;1;3]	Time period : 92-94 Geo : Western Europe Average technology	1
E	[1;2;**2**;1;3]	Time Period : post 1999 Geo : Western Europe Polymerisation under normal pressure Survey of 24 European sites	2

Table 3 : DQA of 5 sources related to HDPE production

4.3 - Comparison of HDPE and LDPE alternatives integrating quantified uncertainty

The second experiment consisted in comparing two alternative raw materials used to produce grocery bags. The first one is composed of HDPE while the second is composed of LDPE. The first bag is characterised by a single use until its disposal while the second is reusable, and it is assumed that the rate of reuse is equal to 3.
In order to satisfy the functional unit, i.e. the packaging of 9000 liters per year, 643 bags are necessary for the HDPE alternative compared to 82 for the LDPE.
The unit amount of LDPE per bag is 44 g. For HDPE bags, the total production is divided in equal proportions between three suppliers and the unit amount of plastic per bag varies from 5.31 to 6.12 g.

A first impact assessment was performed excluding the uncertainty concerning the amount of material (Figure 2). The results illustrate that the use of HDPE is the best alternative regarding GWP, while the opposite is true for acidification. The interpretation is limited to a comparison of two single values in this case.
A second experiment was then performed and the variable amount of HDPE resin per bag mentioned above was taken into consideration. The overall production is indicated in Table 4.

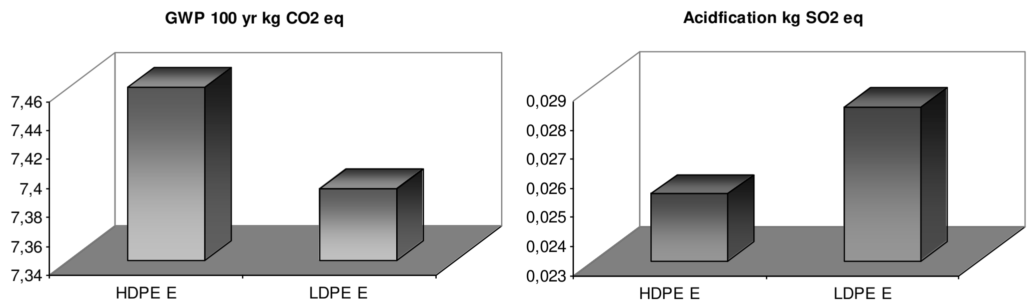

Figure 2: Comparison of the environmental impact assessments of two types of grocery bag production with respect to GWP and acidification respectively

Producer	X	Y	Z
Mass per bag (g)	6,12	6,09	Mean: 5,91 Min: 5,35 Max: 6,12
ratio	1/3	1/3	1/3
Assumed distribution	-	-	Triangular distribution

Table 4 : Characteristics of the overall HDPE production

The different masses indicated in Table 4 were determined from measurements. For the two producers X and Y, the number of bags sampled was not specified. Concerning producer Z, the measurements were performed with 11 bags and the 11 measurements are not reported in the study; only the mean, lower and upper values were used. Although the sample size is statistically insufficient to perform such a method, we decided to integrate and propagate the uncertainty through Monte Carlo Simulation. Indeed, LCA frequently suffers from a lack of data and LCI are often composed of this type of small samples. This observation is representative of the actual situation.
In addition, due to the limitations of sample X, no standard deviation and only range limits were available; it was assumed that the statistical distribution was triangular (Figure 3).
A Monte Carlo simulation was carried out (1000 simulations). It is to notice that we performed this experiment for illustrative purpose. First, we only estimated the impact of a single parameter, i.e. the amount of raw material and secondly, the use of 1000 runs for Monte Carlo simulation is insufficient and should strongly be increased to provide reliable results when dealing with more input variable data (Vose 2008).
These results are summarised in Figures 4 and 5. In order to estimate the real influence of the inclusion of uncertainty, we focus on 2 alternatives, HDPE E and LDPE respectively. Indeed, the impact assessment results are very close compared to the other alternatives and correspond to alternatives modelled in the original study. The results for the two alternatives included in the original LCA are presented in Figure 6. Figure 2 proposes the initial impacts obtained with single values, while Figure 6 integrates the uncertainty related to input data.

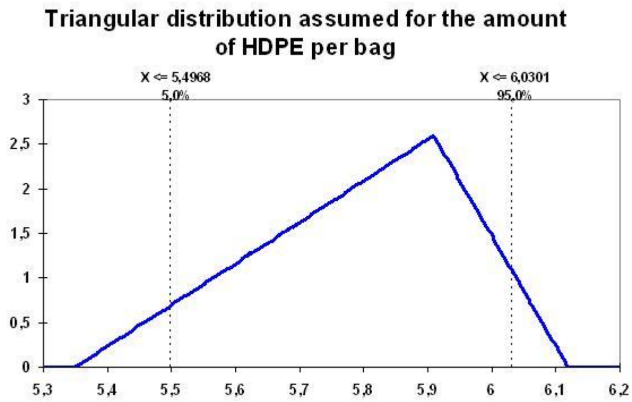

Figure 3: Triangular distribution assumed for the amount of material per bag – producer Z

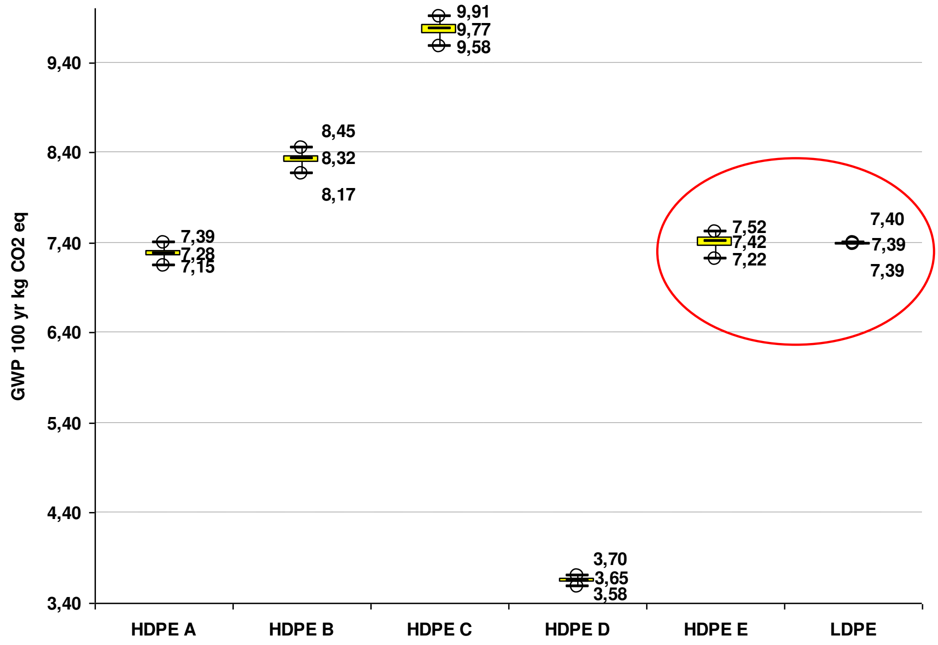

Figure 4: Global Warming Potential (100yrs) of the 5 HDPE and LDPE alternatives including uncertainty on input data

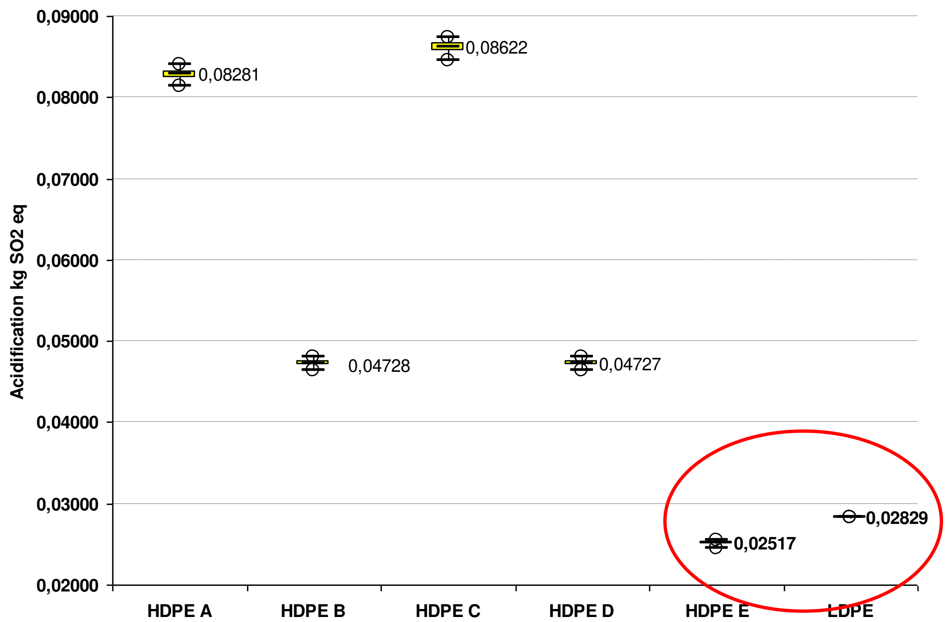

Figure 5: Acidification of the 5 HDPE and LDPE alternatives including uncertainty on input data

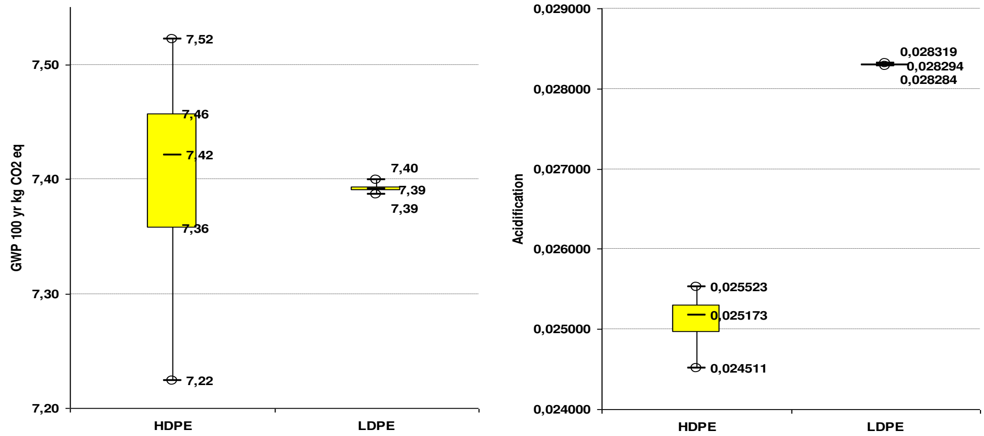

Figure 6: Impact assessment of two HDPE and LDPE productions respectively integrating uncertainty on the amount of material per bag through Monte Carlo simulations.

Once the uncertainties had been integrated, it was no longer easy to identify the best alternative. Previous results had shown that HDPE was more impacting than LDPE with respect to GWP. The results from the new simulation were not so conclusive. Indeed, it appears that the probability that the HDPE is more impacting than the LDPE is not 100%. In contrast, for acidification, the simulation results were similar to those of the previous experiment.

In order to complete the test conducted and define the probability that HDPE has a higher GWP impact than LDPE, we performed another Monte Carlo simulation. In this case we calculated the relation HDPE minus LDPE. The results indicated that HDPE would be less impacting than LDPE; with a probability of 17% (i.e. HDPE is less impacting than LDPE in 17% of the 1000 simulations).

Applying this quantitative approach can provide decision-makers with additional information. In the case of acidification, the initial results were confirmed and the integration of uncertainty was inconsequential to the final result. In contrast, for the global warming potential, the final result was more ambiguous and the influence of uncertainty was higher. This approach appears very useful when comparing alternatives with very similar environmental impacts. Moreover, its implementation should be very helpful for sensitivity analysis or when the final objective is a real quantification of environmental impacts.

5 - Discussion: Usefulness of such approaches

5.1 - Advantages and drawbacks

5.1.1 - Qualitative approach

The implementation of such approaches to deal with LCI uncertainty has advantages but also several limitations.

First, the systematic implementation of data quality assessment using Metadata and the pedigree matrix during data collection guarantees that the LCI will be in accordance with the data quality objectives. Moreover, this approach provides a scan of the dataset. Weaknesses and any lack of data are easily identified. This could be very helpful when new data collection is required. The necessary information is immediately located and the new data collection can focus exclusively on it. The time consumed to build the LCI is then optimised. This is a real advantage, given that LCI is the most time-consuming step in an LCA.

Finally, as mentioned above, this type of qualitative approach could be used as a decision-making tool. Indeed, many LCI databases are now available. In general they do not only differ in the methodology applied but also in the period, geography and/or technology they are representative of. In this context, a comparison between the available data exclusively based on qualitative criteria appears very valuable to identify the most relevant data with respect to the objectives of the study.

Nevertheless many limitations arise. First of all, DQA results must be exploited carefully. Indeed, they only provide additional information on the quality of the dataset, which needs to be connected to the DQO in order to optimize its usefulness.

In addition, each criterion included in the pedigree matrix corresponds to a new data to be collected. The use of five criteria as proposed by Weidema consequently increases the size of the dataset by a factor of five. This means that time resources allocated to data collection and data management are also impacted.

5.1.2 - Quantitative approach

The quantification of uncertainties and their propagation through Monte Carlo simulation provide additional numerical information concerning the variability of the final result. The main advantage is the integration and propagation of all uncertainties if known, throughout the whole procedure. In addition, the results showed that impact assessment is more precise when comparing alternatives with similar environmental performances. Finally, it appears very practical when performing sensitivity analyses.

Nevertheless, the implementation of such a method also has many limitations. In general, sample sizes are too small to identify statistical parameters such as the mean, the standard deviation and in general the type of distribution. Moreover, given that the LCI is often composed of a large quantity of data, the identification of distribution parameters for each of them is very time-consuming.

5.2 - A proposal to use a qualitative, quantitative or mixed approach depending on the initial purpose of LCA

These two qualitative and quantitative approaches are complementary to deal with data uncertainty in LCA. Indeed, they provide an evaluation of the overall uncertainty based on both qualitative and numerical information. A restricted use of one of these two approaches does not cover the overall uncertainty, but is it really useful to implement a mixed approach, combining successively qualitative and quantitative approaches, as proposed by Coulon (1997) according to the LCA objectives?

In order to discuss the usefulness of such a method, we propose a matrix (Table 5) cross-linking the different LCA goals (ISO 1 2006) (ISO 2 2006) (Grisel, Osset 2004) (Blouet, Rivoire 1995) and the choice of a qualitative, quantitative or mixed approach. Several proposals are briefly discussed and acceptable uncertainties are estimated.

The final purpose of an LCA directly impacts data collection and the LCI. Consequently, the goal of the study also impacts data quality and the depth of analysis. Keeping in mind that the major limitations of LCA are data availability and the time required to collect data, the definition of a pre-defined strategy to manage uncertainty should help avoid wasting time searching for irrelevant information.

We propose in the table 5 to establish a strategy to address uncertainty at the first step of LCA according to final objectives. Dealing Systematically with uncertainty in LCA can be perceived harder and much more time-consuming. Indeed, these additional steps required additional data that mean additional effort to collect and manage the database. Some of these informations can also be harder to collect, unavailable or inexistent.

Moreover, the inclusion of uncertainty in LCA results does not seem to be always relevant. Indeed, LCA objective does not always suggest a high degree of details. We assume that uncertainty must be treated as a risk level combining the degree of LCA uncertainty and the degree of acceptable uncertainty defined by LCA objective.

Objectives			Qualitative approach	Quantitative approach	Acceptable level of uncertainty	Comments
Private sector	Internal use	1 - Better Knowledge of the system under study	Yes	No	Means	In general such a goal involves identifying the most impacting sub systems or life cycle steps
		2 - Design choices in environmental purpose (optimisation)	No	Yes	Means – low	Optimisation comparing existing systems to potential alternatives. The quantitative approach could be useful to classify the different options. In contrast, DQA does not seem relevant if the study is based on data directly generated by the company, assuming that acquisition methods are similar from one alternative to another
		3 - Reducing environmental impacts (end-of-pipe, strategy)	Yes/ No	Yes / No	Means – low	A mixed approach appears relevant. If the LCI is not fully based on internal data, the qualitative approach could prevent the use of inaccurate data. In addition, the quantitative approach could be implemented if an impact reduction is targeted with quantified objectives
		4 - Reducing environmental impact in new product or process design	Yes	No	High	Acceptable uncertainty is very high. Design choices are not yet defined. The quantitative approach does appear useful. The qualitative approach guarantee a good data quality
	External use	5 - Search for competitive advantage using external communication	Yes	Yes Restricted to alternatives with similar impacts	Means	For such purposes, communication usually focuses on advantageous results. The quantitative approach could be useful in the case of an Environmental Product Declaration or to compare alternatives with similar impacts
		6 - Opening discussions with economic partners (strategy)	Yes	Yes / No	Means – low	DQA guarantees the quality of the dataset. The quantitative approach could be relevant to compare alternatives with similar impacts or if quantified objectives are set
		7 - Opening regulatory discussions (government, NGOs, trade associations)	Yes	Yes / No	Means –low	
Public sector		8 - Definition of environmental policy – regulatory decision tool	Yes	Yes / No	Means - low	
		9 - Public educational tool (awareness raising)	No	No	High	Neither the qualitative nor quantitative approach appears useful for public awareness raising. Usually information is restricted to trends

Table 5 : Proposed use of the qualitative, quantitative or mixed approach depending on the LCA goal

Performing LCA to increase knowledge on a system in order to identify way of environmental improvement does not require the same level of detail and degree of uncertainty than the search of competitive advantage based on a product comparison. In the first case, attempts usually focus on the identification of most impacting life cycle steps and or most impacting material or operation. LCA results don't need to be precise and degree of acceptable uncertainty is means to high. Indeed, the main objective is not to provide a quantitative impact assessment but rather to identify design key point to increase the environmental performance. Consequently a simple data quality assessment, to control that most relevant data are used to perform LCA, seem to be enough to address uncertainty. In the second case, LCA objective is to prove that an alternative is better than another one. Impact assessment quantification is required and the degree of acceptable uncertainty is low. Consequently a quantitative uncertainty approach seems relevant in this case in order to prevent from false conclusion.

This table was drawn using personal communications with designers and LCA analysts. Proposals made need to be validated at present time. Validation is under progress. Both qualitative and quantitative are performed in several LCA with different objectives. The main goal is to identify which is the best strategy with respect of LCA objectives.
The expected result is to optimise the time consumed to collect data, and still reach the data quality objectives and the appropriate depth of analysis in accordance with the final purpose of the study.

6 - Conclusion and perspectives

Even if Life Cycle Assessment is a well-established method to assess the environmental impacts of products, services and processes, it suffers from several uncertainties. Different typologies have been proposed since the 1990s. The LCI was identified as the step containing most of the uncertainty. In order to manage these deficiencies, several methods have been developed that can be classified in two main groups: the qualitative approach and the quantitative approach.
Experiments were conducted to estimate the usefulness of such approaches. Each one has advantages but also limitations. Nevertheless, they are complementary, since they do not treat the same type of uncertainty nor provide the same additional information.
Previous works dealing with the subject proposed a joint implementation of both qualitative and quantitative approaches to address overall uncertainty. However, given that the major limitation in LCA implementation is data availability and the time consumed to collect the LCI, is it really useful to apply a mixed approach?
The last part of this article attempts to help answer this question, taking into consideration the main purpose of the study.

In order to consolidate the results of this paper and define the effective usefulness of each approach in accordance with LCA objectives, it would be interesting to apply both qualitative, quantitative and then mixed approaches while performing LCAs with different final purposes and then estimate the influence on final results. Moreover, a correlation between the additional information obtained, its usefulness regarding LCA objectives and the time consumed to collect and integrate uncertainty would be very helpful. This work is currently in progress. A real optimisation of the time consumed to collect and include uncertainty is expected.

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