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Data certification for LCA comparisons: Inventory of current status and strength and weakness analysis

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Summary

Analysis

During the last decade many LCA-studies (Life Cycle Assessment) have been carried out with different successes and impact with respect to their results. It is important for the future of the LCA practice that the results become generally regarded as relevant, reliable and uncontroversial as possible.

In order to communicate more accurately on the results of LCAs, more information is required about the quality of the data input. Everyone can understand that comparisons of products or materials, based on LCAs presenting different levels of data quality, will result in endless discussions. If a well-documented study was to be compared to its less complete analysed counterpart, biased conclusions would favor the latter.
Therefore, there is a need to have a procedure describing how to handle data quality issues in LCAs.

A procedure has to be developed making certified basic inventory data obligatory for the execution of LCAs ensuring the outcome of such studies is reliable.Limits have to be formulated beyond which the certified data cannot be used; for instance when the results of LCA comparisons become a subject for policy making.

In this report two executed inventories are described:
– An inventory of the developments in the area of “data quality and certification”.
– An inventory of the strengths and weaknesses of modelling and coupled data collection currently applied by LCA practitioners to different packaging systems.

In the area of data quality the activities of SETAC, ISO and others are analysed and evaluated. The generation of quantitative and qualitative data quality indicators is the basis for ongoing developments with regard to data quality.
The ISO 14040 standards are of great importance. The following quality indicators are described in these standards:
– Time related coverage
– Geographical coverage
– Technology coverage
– Precision, completeness and representativeness of the data
– Consistency and reproducibility of the methods used
– Data sources and their representativeness
– Uncertainty of the information

Preferably the quantitative indicators (precision, completeness and uncertainty) should be given in a quantitative expression. For the data sources and their representitveness a more qualitative expression (for instance by means of a pedigree matrix) is a possible solution.

With the help of these selected quality indicators two European LCA key studies are analyzed in more detail: The German Prognos and the Danish Chalmers studies. A strengths and weaknesses analysis is conducted.

The Chalmers study scores low with respect to the data quality indicators regarding the ISO 14040 standards. This low performance is mainly due to the absence in the report of the necessary data to assess the data quality indicators. A clear evaluation of the coverage of the data is not reported.

The Prognos study has a better performance, though for a number of indicators (such as precision, completeness and representativeness of the data or uncertainty of the information) the information needed to assess the data quality is missing.

Conclusions

Data quality is becoming more and more an issue in the area of LCI (Life Cycle Inventory) and LCA. Insufficient data quality is the most commonly reported problem related to data uncertainty in LCAs. Uncertainty in the LCI and other data applied in LCA calculations has an important impact on the final calculation results and major implications for the significance of observed differences between compared systems.

The two evaluated studies show insufficient data quality analyses and from that point of view it is not advisable to support policy making with uncomplete study results.

Data certification is a way to ensure a standard data quality level, however certification has not yet been applied to LCI or LCA data. Increasing the quality of data will increase the reliability of LCA results and will improve the quality of the instrument. Data certification should be able to bring full transparency of the data and modelling.

Recommendations

- The quality of data has to be ensured by a process of reviewing and verification.
- A data certification procedure has to be implemented to guarantee a certain data quality level and a guideline should deal with the occurance of low quality data.

- A procedure must be developed to describe how to handle the case of low quality data, as well as the case of differences between the levels of quality of the different data. Important aspects of the procedure will be:
  - Check of the completeness/reality of the model that simulates the chain to be analyzed (input, output, process descriptions, boundaries);
  - Check of the reliability/quality of the (used) data;
  - Check of the mass/energy balances of the observed (production) processes.
- A balanced application of certified data in combination with a sensitivity analysis will strongly improve the outcome of an LCA analysis.
- Two key aspects are important to get the procedure running:
  - A system has to be introduced in order to get industrial sectors to deliver the LCI data of their processes. The quality of these data has to be assessed by a certification bureau. Dependent of the outcome of this assessment a certification body will issue a certificate for the overview of the process data.
  - The certification procedure has to become a part of the ISO 14040 series. A discussion with the ISO bureau has to be started to realize such an inclusion.

Even when a data certification procedure and a sensitivity analyses complete LCA studies, the results impact has to be combined with the outcome of economic and social analyses with regard to policy making. It is recommended to integrate environmental, economic and social analyses for society relevant studies.

Table of contents

1. Introduction

For more than 10 years LCA-studies have been carried out with different successes and impact with respect to the results. It is important for the future of the LCA practice that the results become generally regarded as relevant, reliable and uncontroversial as possible.

TNO analyzed and evaluated a number of European key-studies regarding the Life Cycle Analysis of several one-way and refillable beverage packaging systems [15, 24]. One of the main conclusions of these studies is that the final results of these LCAs are greatly influenced by data quality and therefore do not enable objective comparisons to be made.

It is therefore relevant when communicating on the results to know more about the quality of the applied data. Everyone knows that LCA comparisons of products or materials presenting data quality, differences will result in a lot of discussions.

With these aspects in mind, there is a need to have a procedure on how to handle quality of data in LCAs. A comparison between a well-documented alternative and a less complete analysed counterpart will be biased towards favouring the latter.

Data collection for life cycle inventories (LCI) is still a critical factor for successful execution of LCAs. Especially data linked to the consumption of resources use and emissions can raise problems. Actual monitoring of the use of resources and emissions is not a common practice. Some manufacturers do not provide the necessary data for LCAs and if data are available for the public, these tend to be outdated or may not reflect current technologies. It is important to know to what extent the outcome of an LCA is affected by data uncertainties in the inventory.

From that point of view APEAL requires a procedure to be sure LCAs are executed in the right way and that the data used are reliable or that the output of a sensitivity analysis gives insight into the uncertainties of the used data. APEAL has commissioned TNO Environment, Energy and Process Innovation (TNO-MEP) to carry out a study with the aim to develop the afore mentioned procedure.

The objectives of the present project are:
- *Inventory of the developments in the area of "data quality and certification".* Among others the activities of different ISO 14000 workgroups and the SETAC group "data availability and data quality" will be analysed and evaluated.
- *Inventory of the strengths and weaknesses of current process modelling and coupled data collection executed by LCA practitioners with regard to the different packaging materials.* The results give insight into the completeness of the applied data, the kind of data gaps and the kind of impacts data uncertain-

ties generated. The considerations are not only related to the judgment of the data and its values, but also to the modelled processes/systems for which the data are generated.

The status and developments in the field of data quality and data certification will be described in chapter 2. Especially the use of data quality indicators is analysed and evaluated.
In chapter 3 more attention is paid to the strengths and weaknesses of an analysis related to data quality in data collection and data modelling. As an example two European key studies are deeply evaluated with regard to these aspects.
Overall conclusions and recommendations are given in chapter 4.

2. Status quo and developments in the field of data quality and data certification

2.1 Introduction to data quality and model quality

Quality is a much-used noun; its literal meaning is however not strictly defined. In the context of data and model quality it can be described as 'a degree or grade of excellence'. In ISO 14041 [10] data quality is defined as:

Characteristic of data that bears on their ability to satisfy stated requirements

The quality of LCA results depends on the quality of the input data and the quality of the used methodology or model:

$$Q_{\text{input data}} * Q_{\text{methodology}} = Q_{\text{LCA results}}$$

LCA data quality can be defined as the degree of confidence in individual input data or the data set as a whole [1]. An important part of this data set is formed by the LCI data. The topic of data quality, and especially that of the LCI data, will be dealt with in more detail in the following paragraphs.

Model quality is linked to **model uncertainty**; which is the uncertainty that is introduced by making use of models to represent the systems and their environmental effects under study. Models have to be made as the environmental system is over-complex and only a limited number of relationships can be established. Models are also used to predict for instance the toxicity of a certain substance for humans. Related to the model uncertainty is the **decision rule uncertainty**. This type of uncertainty is introduced whenever a choice has to be made to assess a certain impact. The aquatic ecotoxicity potential can be calculated using several approaches. These approaches will deliver results that most likely vary from each other

2.2 Status quo and developments in the field of data quality

In this paragraph the status quo and ongoing developments specifically in the field of data quality will be shown. The organisations SETAC and ISO will particularly be in focus as they have a strong influence on the development of LCI and LCA.

2.2.1 SETAC

SETAC is the Society of Environmental Toxicology and Chemistry and has influenced the development of LCA since a number of years. It is an independent, non-

profit professional organization that provides a forum for individuals and institutions engaged in:
– Study of environmental issues;
– Management and conservation of natural resources;
– Environmental education;
– Environmental research and development.

In October 1992, a workshop was held by SETAC [1], which addressed data quality in LCA. Results of the workshop have been discussed in the previous chapter. In April 1998 SETAC-Europe formed a working group called 'Data Availability and Data Quality'. The goal of the working group was to suggest improvements to the efficiency and quality of data collection [4].

SETAC [1] divided data quality in quantitative as well as qualitative data quality indicators as is shown in Table 1.

Table 1 LCA data quality indicators [1].

Quantitative data quality indicators	Qualitative data quality indicators
Precision	Consistency
Completeness	Applicability/suitability
Distribution	Comparability
Homogeneity	Representativeness
Correlation structures	Identification of anomalies
Uncertainty	Reproducibility
	Accessibility/Availability

2.2.1.1 Quantitative data quality indicators

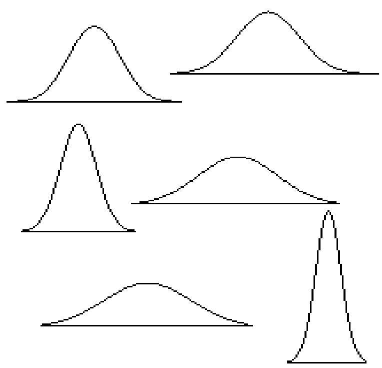

Figure 1 Examples of distribution of values around the mean.

Precision is a measure of the variability within the set of measured data values, it can be expressed as a statistical mean and variance. If the value of a parameter is only based on one measurement the precision cannot be quantified.

Completeness is the number of sampled data points compared to the maximum number of possible data points. It is expressed as a percentage, if for instance 10 of the 50 possible points have been sampled the completeness is 20%.
Especially natural systems show a variation in **distribution** of the value of a parameter (i.e. the metal content of ores). These values have a certain stochastic distribution, as for example the normal or Poisson distribution (see Figure 1). Knowledge of the distribution is especially important when statistical analysis must be made.
The distribution of the value of a parameter may in special cases show two or more distinct peaks. In that case one cannot speak of **homogeneity** in the data.
Correlation structures appear when for instance the value of a parameter is not randomly dispersed over a certain area but is related to its geographical position. The grade of an ore shall show such a correlation. Correlation structures may also be seen regarding time or technology. When these correlations exist it is at least important to know to which region, period or technology the data are related.
Uncertainty is caused by a number of errors: measurement errors (resolution of the measurement), random errors due to the sampling method used, systematic errors due to biases in the experiment or sampling method and errors made while estimating a parameter value. Data gaps (the complete lack of data) also contribute to the uncertainty within a study [3]. Uncertainties may or may not have a significant effect on the outcome of a study.

2.2.1.2 Qualitative data indicators

Consistency is a measure of how uniformly the methodology of the study has been applied to the components of an analysis. Inconsistencies arise when for instance the system boundaries are not kept the same for all processes used within the system under study. Checking the consistency within a study is performed within a peer review.
Applicability/suitability refers to the relevance of a data set for the purpose of the study. To be able to assess this indicator it is important to know the data source, age of the data or region from which the data stem.
A high degree of **comparability** is obtained when the boundary conditions, assumptions, data categories et cetera have been documented to allow for comparison with other LCA studies on the same topic, or within an LCA study between materials.
The degree in which data values used in the study represent that of the system under study is called the **representativeness**.
Anomalies are outliers or extreme values within a data set. They may be identified by statistical analysis or by expert judgement. They may or may not be removed from the data set, though in both cases their appearance must be mentioned in the study.
A study is fully **reproducible** when another researcher can recalculate the study's results based on the information that has been given about the study.

Accessibility measures whether the information on which the study has been based is accessible to internal or external experts. **Availability** is the degree to which the data are available to the practitioner of the study. Available data do not always have to be accessible to external parties as the data may be confidential.

2.2.2 ISO

The International Organization for Standardization (ISO) is a worldwide federation of national standards bodies. The mission of ISO is to promote the development of standardization and related activities in the world. The ISO 14040 series [9], [10] deals with life cycle assessment. ISO 14040 [9] states in article 5.1.2.3. that the following data quality requirements should be specified and addressed:
- Time-related coverage;
- Geographical coverage;
- Technology coverage;
- Precision, completeness and representativeness of the data;
- Consistency and reproducibility of the methods used;
- Data sources and their representativeness;
- Uncertainty of the information.

In the ISO standard 14041 [10], which deals with the inventory analysis the data quality requirements, are given in article 5.3.6. and the aforementioned requirements are specified to more detail. However no specific requirements are given, no maximum age of the data for studies regarding the current situation or a specific time period are given. An important remark is that the data quality requirements shall be related to the goal and scope of the study.

Data quality is also an important issue in the to be published ISO technical specification 14048 [11]. Sample volume, valid technology, area and time span and data distribution are used as indicators.

2.2.3 Other organizations

NUSAP net is an open web community dedicated to uncertainty and quality in environmental assessment, with a special focus on the further development, application and dissemination of the NUSAP method. The notational system "NUSAP" by Funtowicz and Ravetz [6] enables the different sorts of uncertainty in quantitative information to be displayed in a standardized and self-explanatory way. Since the management of uncertainty is at the core of the quality control of quantitative information, the system "NUSAP" also fosters an enhanced appreciation of the issue of quality in information.
The NUSAP system is based on five categories, which generally reflect the standard practice of the matured experimental sciences. The name "NUSAP" is an acronym for the categories (**N**umeral, **U**nit, **S**pread, **A**ssessment, **P**edigree). The cate-

gory **N**umeral will usually be an ordinary number, but when appropriate it can be a more general quantity, such as the expression “a million” (which is not the same as the number lying between 999,999 and 1,000,001). Second comes **U**nit, which may be of the conventional sort, but which may also contain extra information, as the date at which the unit is evaluated (most commonly with money). The middle category is **S**pread, which generalizes from the “random error” of experiments or the “variance” of statistics. Although Spread is usually conveyed by a number (either + , % or “factor of”) it is not an ordinary quantity, for its own inexactness is not of the same sort as that of measurements.

The NUSAP expression has also a more qualitative side, which is found in the last two letters of the acronym. The category **A**ssessment provides a place for a concise expression of the salient qualitative judgements about the information. In the case of statistical tests, this might be the significance level; in the case of numerical estimates for policy purposes, it might be the qualifier “optimistic” or “pessimistic”. Finally there is **P** for Pedigree. In the NUSAP case, the pedigree is an evaluative description of the mode of production (and where relevant, of anticipated use) of the information. An example of a pedigree matrix is given in Table 2. Higher scores reflect to lower data quality.

Table 2 Pedigree matrix for emission data [8].

Score	Proxy	Empirical	Method	Validation
1	An exact measure of the desired quantity	Controlled experiments and large sample direct measurements	Best available practice in well established discipline	Compared with independent measurements of the same variable over long domain
2	Good fit or measure	Historical/field data uncontrolled experiments small sample direct measurements	Reliable method common within est. discipline Best available practice in immature discipline	Compared with independent measurements of closely related variable over shorter period
3	Well correlated but not measuring the same thing	Modelled/derived data Indirect measurements	Acceptable method but limited consensus on reliability	Measurements not independent proxy variable limited domain
4	Weak correlation but commonalities in measure	Educated guesses indirect approx. rule of thumb est.	Preliminary methods unknown reliability	Weak and very indirect validation
5	Not correlated and not clearly related	Crude speculation	No discernible rigour	No validation performed

In the USA the U.S. LCI Database Project has been launched. Its purpose is to develop selected product LCI data for use by the public. One working paper of this project is devoted to data quality [6]. In Table 3 the pedigree matrix that is part of this working document has been given.

Table 3 Pedigree matrix with three data quality indicators ([6] from Weidema, 1998).

Score	Temporal correlation	Geographical correlation	Further technological correlation
1	Less than 3 years of difference to year of study	Data from area under study	Data from enterprises processes and materials under study
2	Less than 6 years difference	Average data from larger area in which the area under study is included	Data from processes and materials under study but from different enterprises
3	Less than 10 years difference	Data from area with similar production conditions	Data from processes and materials under study but from different technology
4	Less than 15 years difference	Data from area with slightly similar production conditions	Data on related processes or materials but from same technology
5	Age of data unknown or more than 15 years of difference	Data from unknown area or area with very different production conditions	Data on related processes or materials but from different technology

Under the Emission Inventory Improvement Program (EIIP) of the US EPA, special attention was directed to the quality assurance and quality control procedures. One of the tools is **DARS** [5]. The Data Attribute Rating System (DARS) was originally developed as a research tool for rating national and global greenhouse gas inventories. The DARS score is based on the perceived quality of the data. This method is thus basically of a qualitative nature. Scores are assigned to four data attributes:

– Measurement/method
– Source specificity;
– Spatial congruity;
– Temporal congruity.

The key to correctly scoring the **measurement/method** attribute is to remember that it deals explicitly with measurement. The presumption is that the best results are usually obtained by direct measurement of either emissions (either by source testing or continuous emission monitors) or by measurement of surrogate parameters that have a strong, statistically documented correlation with the pollutant of interest.

The **source specificity** attribute concerns how specific the original data is to the source being estimated.

The **spatial congruity** attribute deals with the spatial scaling of factors and activity data that is common to inventories.

The **temporal congruity** attribute describes the match between the data and temporal scale of the inventory.

Each of the four attributes is scored on a scale from 1 to 10 by using decision trees [5].

2.3 Examples of handling data quality

The International Iron and Steel Institute (IISI) launched in 1996 a comprehensive data collection project, known as the IISI Worldwide Life Cycle Inventory (LCI) Study for Steel Products. An integral part of the project was the development of a common worldwide methodology [12] for collating and evaluating steel product LCI data.

Data sources for site data were defined in three categories:
- Site specific measured or calculated data;
- Literature based information;
- Data from other sources, e.g. extrapolated data from other steel sites.

Four data quality categories were specified for the collected LCI data:
- Measured data from continuous or spot measurements on site;
- Calculated data where the value was calculated from empirical relations, e.g. using emission factors or from mass balances;
- Estimated data where the value is estimated from approximations;
- Unknown, this goes for all data from literature or other sources where no classification to the foregoing three categories is possible.

In the large Dutch project considering the environmental properties of the life cycle of building materials MRPI©, data quality was one of the issues[19]. An example of the qualitative data quality description is given in Table 4.

Table 4 Example of the presentation of data quality indicators in the Dutch LCA project for building materials MRPI© [19].

	Geographical coverage	Time period coverage	Technology coverage	Precision	Comprehensiveness	Representativity	Consistency	Reducibility
Processes at manufacturers								
Production process	Germany, France, The Netherlands	1998 – 1999	Specific	Good	Good	Specific; good	Good	Good/ moderate
Transport to building place	Germany, France, The Netherlands	1990 – 1996	Generic	Good	Good	Generic; good	Good	Good
Processes at suppliers								
Raw materials	Europe	1990 – 1996	Generic	Good/ moderate	Good	Generic; good	Good	Good/ moderate
Packaging materials	Europe	1990 – 1996	Generic	Good	Good	Generic; good	Good	Good/ moderate
Background processes								
Electricity generation	Germany, France, The Netherlands	1996	Generic	Good	Good	Generic; good	Good	Good
Natural gas production	The Netherlands	1996	Generic	Good	Good	Generic; good	Good	Good
Transport (generic)	Europe	1990 – 1996	Generic	Good	Good	Generic; good	Good	Moderate
Landfill (IBC)	The Netherlands	1995	Generic	Good	Good	Generic; good	Good	Good
Incineration (AVI)	The Netherlands	1995	Generic	Good	Good	Generic; good	Good	Good
Recycling waste material	The Netherlands	ca. 1995	Specific	Good	Moderate	Generic; good	Good	Moderate

In MRPI® both quantitative as qualitative data quality indicators (see Status quo and developments in the field of data quality) have been used. However not all of the quantitative indicators have been described quantitatively as this was not obligatory, **precision** is indicated by a qualitative indication as good or moderate.

SPOLD, Society for Promotion of Life-cycle Assessment Development, has developed a common format for the exchange of life-cycle inventory data, allowing data to be understood, compared and exchanged, disregarding how they are stored in their original database. In this format a number of data quality indicators is used:

- Time Period
- Geography
- Technology
- Representativeness
- Uncertainty type
- Coefficient of Variance
- Data Availability

The number of samples and the part of the system or population that has been sampled, describe the **Representativeness** of the data.
The **Uncertainty type** is a description in terms of the type of distribution. The most typically used distributions for environmental and economic data are: Binomial, lognormal, normal, range (min/max), triangular and uniform.
The **coefficient of variance** is an expression of variance defined as the standard deviation (the square root of the variance) divided by the mean value (expressed as a percentage).
Data availability is described in qualitative terms: Not available, Qualitative info available, Quantitative info available.
Data quality is further addressed by the validations of the data that have been carried out. These may be on site validations, calculation of mass balance, cross checks and other validations.

In SimaPro©5.0 [13], the software used by TNO-MEP to calculate LCAs, data quality indicators (DQI) have been incorporated into the programme. SimaPro© 5.0 uses the following DQIs:
- Time period;
- Region;
- Type of technology;
- Representativeness;
- Allocation;
- System boundaries.

There are three data quality indicators reserved for allocation. The first two refer to allocation in multiple output processes, the third field refers to waste treatment processes.
For system boundaries SimaPro© distinguishes between three different ways to describe system boundaries:
1. Cut-off criteria;
2. First, second or third order;
3. Boundary with nature.

Clearly a number of efforts have been undertaken to ensure a certain level of data quality in LCA. The international standard ISO 14040 is followed to a great extend.

2.4 Managing data-related uncertainty in LCA studies

Uncertainty in the LCI data and other data used in LCA, such as % of recycling, % of close loop recycling, has an impact on the reliability of the results and on the significance of the observed differences between compared systems within a LCA. A number of techniques exist to examine the effect of uncertainty in the input data on the outcome of the LCA model:

1. Sensitivity analysis (predict the effect of changes in input on the output);
2. Uncertainty propagation analysis (calculate uncertainty in output due to uncertainty in input);
3. Uncertainty analysis (compare the importance of uncertainty of a parameter in terms of its relative contribution to output of the model).

Handling data uncertainty should be part of an LCA, though in practice this aspect may not get the attention it needs [22]. In the ISO 14041 standard [10] uncertainty in the LCI data is brought to the attention of the LCA practitioners. The 14041 standard gives some approaches to deal with uncertainty:
1. Sensitivity analysis on significant inputs, outputs and methodological choices;
2. Using ranges and/or probability distributions instead of single values;
3. Data quality assessment.

Data inaccuracy, besides the lack of data, is the main cause of data uncertainty. The SETAC working group on data availability and data quality presented in one of its papers a scheme for the analysis of data inaccuracy [3]. The performing of stochastic modelling, for instance a Monte Carlo simulation as was done by TNO [15] for the UBA II study [16], is presented as a promising technique for uncertainty analysis [3]. Ideally, for conducting a Monte Carlo simulation parameters describing the uncertainty distributions, like parameters that describe the form of the distribution of a certain property, are needed. Using an artificial standard sensitivity/uncertainty range for all parameters, as was also done by TNO [15], is seen as a possible first step in the analysis of data inaccuracy [3]. The next step is then to analyse in further detail the uncertainty within the most important parameters.

However, the technique of uncertainty analysis applied to LCI is still in its infancy [10]. This especially applies to the quantitative analysis of uncertainty. In LCA studies (both articles and reports) uncertainty is mentioned in roughly half the cases [22], a quantitative or qualitative analysis has however only in 5% of the cases been executed.
Insufficient data quality appears to be the most commonly reported problem related to uncertainty in an LCA study [22]. Huijbregts et al. [3] point that data uncertainty analysis shows the influence of data uncertainty on the LCA results, however the reduction of data uncertainty is only obtained by additional research.

2.5 Status quo and developments in the field of data certification

Data certification is slowly becoming an issue. Examples are mainly found in the world of GIS (Geographical Information Systems) [14].

The assurance of data quality is often secured by executing a critical review. The U.S. LCI Database Project sees critical review as essential in reducing uncertainty and errors in LCI data[6]. A critical review is also part of the ISO standards. In ISO

14040 article 7 is dedicated to the process of critical review. The critical review focuses on both the used LCA methodology, the interpretation of the LCA results, the LCA report and the data used. The data must be appropriate and reasonable in relation to the goal of the study.

2.6 Résumé: data quality in relation to APEAL

Data quality is of interest to APEAL as (comparative) LCAs have been made and probably will be made in the future in which steel plays a role as one of the packaging materials. The quality of the LCI and LCA data influence the outcome of these studies and may also influence the mutual positions of the system under study.

From paragraph 2.2 it may be clear that the interpretation of data quality is diverse and knows a large number of data quality indicators. However, some aspects can be considered as having an overall importance. Of great importance are the standards from the ISO 14040 series [9], [10] in which the following data quality indicators are given:
- Time-related coverage;
- Geographical coverage;
- Technology coverage;
- Precision, completeness and representativeness of the data;
- Consistency and reproducibility of the methods used;
- Data sources and their representativeness;
- Uncertainty of the information.

Preferably the quantitative indicators (**precision**, **completeness** and **uncertainty**) should be expressed in a quantitative expression. For the data sources and their **representativeness,** a pedigree matrix seems to be a possible solution. Expressing values as a mean with accompanying coefficient of variation and for instance the 95% confidence limits gives a quantitative indication of the uncertainty in the data.

In Table 5 a proposition is given of the data quality indicators that should at least be included in LCI data sets. The pedigree matrices that are used to indicate the quality of a number of qualitative indicators are given in Appendix 1.

Table 5 Data quality indicators that should be incorporated in LCI and the proposed implementation of these indicators.

Data Quality Indicator	Implementation	Remark
Time-related coverage	- Start date of valid time span; - End data of valid time span; - Deviation from intended period.	 - Pedigree matrix
Geographical coverage	- Area name; - Country name. - Deviation from intended area	 - Pedigree matrix
Technology coverage	- Technology description; - Included processes; - Deviation from intended technology	 - Pedigree matrix
Precision, completeness and representativeness of the data	- Sampling procedure; - Number of samples; - Absolute sample volume; - Relative sample volume; - Representativeness for intended process	 - Pedigree matrix
Consistency and reproducibility of the methods used	- Description of method for data collection and data treatment	
Data sources and their representativeness	- References used for data collection and data treatment; - Type of reference	 - Pedigree matrix
Uncertainty of the information	- Mean value; - Standard deviation; - Description of specific strengths and weaknesses.	 - e.g. occurrence of data gaps

3. Strengths and weaknesses: analysis related to data quality in data collection and data modelling

The SWOT-analysis will be mainly based on the European key-studies regarding the Life Cycle Analysis of several one-way and refillable beverage packaging systems which TNO earlier evaluated for APEAL [15]. Two key-studies are analysed in more detail with respect to data quality:

Table 6 Selection of LCA key-studies used in the evaluation study of TNO [15].

		Packaging systems		
LCA project	Products	Refillable	One-way	Country
Prognos, [16]	Water, CO^2 and non-CO^2 drinks, wine (storage) Water, CO^2 drinks (direct)	PET, glass	Steel, aluminium PET, glass, carton	D
Chalmers, [18]	33 and 50 cc beverage	Glass, PET	PET, glass, aluminium, steel	DK

The analysis is first based on the data quality requirements that have been defined within the studies. In the second step of the analysis the studies are related to the data quality indicators as proposed by TNO (see 2.6).
For each of the two studies an example of the data quality assessment for packaging steel has been given as an example.

3.1 Prognos study

3.1.1 General

In the study carried out for the German Umweltbundesamt [16] the following objective is given.

> Compiling information on environmentally relevant material and energy flows of those packaging systems with a significant importance in the specified *German* beverage market segments, on the basis of **representative** and **average** framework conditions and comparison of their potential ecological impacts.

In the study, the following requirements have been laid down for data and data quality:

1. Representative for the given geographical, temporal and technological context. Data must be representative for Germany in the reference year 1996. The technology used must be preferably be average technology. If available the contemporary available technology may be used;
2. The data should be generally available and accessible. For background processes data disclosed to the public should be used.

For data considering the distribution of beverages, transport distance and number of cycles of refillable bottles special market studies were conducted to assure the highest quality of the data.

The Prognos study has an appendix [17], which gives for each process used the following data quality descriptors; the type of occurrences in the study are given in brackets:
1. Time-related coverage (specific year, specific period);
2. Geographical coverage (Germany, Europe, region);
3. Representativeness (representative for Europe, Germany, measured data, representative for modern technology);
4. Type of average (weighted, no indication);
5. Data sources;
6. Information regarding data quality (no data gaps known, specific data gap, data reviewed).

Considering the methodology the following indicators have been addressed:
7. Scope of the process (for aggregated data the included sub processes have been given);
8. Allocation (no allocation, allocation unknown, specific allocation).

In Table 7 the strengths and weaknesses regarding data quality in the Prognos study are evaluated using the data quality indicators as defined in the study itself. The strengths and weaknesses are also evaluated (see Table 8) using the data quality indicators as proposed by TNO.

Table 7 The strengths and weaknesses of data collection and quality in the Prognos studies [16], [17].

Data Quality Indicator	Strengths	Weaknesses
Coverage	Temporal and geographical coverage are given	Technological coverage only sporadically indicated
Representativeness		Representativeness is not clearly related to Germany, reference year 1996 or average technology
Type of average	Indication of type of average	Type of weighting of average not always clear.
Data gaps	Indication of data gaps	
Scope of the process	Scope is given for aggregated processes	
Allocation		Type of allocation (mass, economic value, physical property) not always specified.

Table 8 Evaluation of the Prognos study based on the seven proposed data quality indicators.

Data Quality Indicator	Evaluation	Score[1]
Time-related coverage	Valid time span is indicated as specific year (e.g. 1995), or as period (mid nineties or 1989-1990) and sometimes unknown. Deviation of 1996 is not mentioned specifically.	1 – 2; 5
Geographical coverage	Certain processes refer to area outside Germany; representativeness for Germany is not mentioned specifically.	1 – 2; 5
Technology coverage	Technology not specifically mentioned. Included and upstream processes are being mentioned in most cases. Deviation from average technology is not given.	5
Precision, completeness and representativeness of the data	Indicated as single measurement, average of n process. Type of weighting of average not always clear. Representativeness for intended process single measurement, not indicated, representative for specific process, representative for European industry, average process	5
Consistency and reproducibility of the methods used	Method for data collection is only sporadically mentioned. No reproduction of method possible. It is possible that in some cases the method is reproducible from mentioned literature. No indication of reproducibility has been given.	5
Data sources and their representativeness	Data sources have been given, but without indication of representativity. Some sources are confidential.	1-3, 5
Uncertainty of the information	In case a value is an average its mean has been given, however the use of standard deviation or another indicator of the variability has not been given. The occurrence of known data gaps is mentioned. In some cases a review of the data is mentioned. In other cases the overall data quality is given as unknown.	5

1 The meaning of the value can be found in the pedigree matrices given in Appendix 1.

The Prognos study [16] has in general good scores for the time-related, the geographical coverage and the representativeness of the data sources. For the technology coverage the score is low as it is not specifically indicated what type of technology is used for the described process. For the other data quality indicators the score is often low, as the relevant data is not mentioned specifically.

3.1.2 Packaging steel

For the process sheet describing the manufacturing of packaging steel an analysis of the strengths and weaknesses has been made according to the data quality requirements as laid down in the study itself [16].

Table 9 Strength and weakness analysis for the manufacturing of packaging steel in the Prognos study [16].

DQI	Strengths	Weaknesses
Coverage	Germany, 1994	Assumption (as data are obtained from Informationszentrum Weissblech) that average technology is given
Type of average		Unknown
Data gaps	No data gaps known indicated	
Scope of the process	Scope of the process is given for aggregated processes	
Allocation	Indication:‘No allocation’	Allocation is not applied

3.2 Chalmers studies

3.2.1 General

In the main report of the Chalmers study [18], data quality requirements considering technology and other data quality aspects are given. The given requirements considering technology are:
1. The technologies that are actually affected by (changes in) the packaging systems must be included. Average data could therefore not be used;
2. The ideal data are data specific for the current technology;
3. Marginal data —data of unit processes which form the input for the product system through a market— should ideally be used for the production of energy, bulk materials and recycled materials;
4. Long-term marginal technology data —technology that is installed or dismantled due to foreseeable long term changes in production volume— are thought to be the most relevant;

The requirements considering other quality aspects are:
5. Ideally data considering the future state of environmental inputs and outputs should be used (as the study focuses on the future situation), however as these data are only available through extrapolation, the most recent data as possible must be used;
6. The data used must be relevant to the Danish situation;
7. The data must be as precise, complete and representative as possible within the framework of the study. Uncertainty must be minimized;
8. The methods used should be consistent and reproducible;
9. A data quality assessment is only carried out for processes that contribute significantly to the total LCA results.

Ad 1
The first requirement appears to be dealing more with the completeness of the system under study than it does with actual data quality. It can be seen as the **applicability/suitability** indicator. The term average data is not very clear. It probably relates to more aggregated data;

Ad 2
The requirement for specific data relates to the degree in which data values used in the study are representative of the system under study. This is the **representativeness** of the data. It also relates to the technology coverage in ISO terms (see 2.2.2);

Ad 3
The term marginal data/processes is synonymous with the more generally used term of background processes. It addresses both the **applicability/suitability** as the **representativeness** indicator;

Ad 4
The long-term marginal technology data addresses the **representativeness** of the data for future situations;

Ad 5,6
In these requirements is dealt with the **applicability**/suitability, which is in ISO terms translated into time-related coverage and geographical coverage;

Ad 7
Here is dealt with the **precision**, **completeness, representativeness** and **uncertainty** of the data. However no quantitative requirements are given;

Ad 8
The intention was to give for each process, the statistical **uncertainty**, the **completeness** and **representativity,** a qualitative score. For reasons of simplification this was only done for the significantly (however, no quantitative indication is given here) contributing process.

In the data collection procedure four priority groups were established, ranging from updated process specific data to data from literature. **Precision, completeness and representativity** were included in the data format.

Based on the foregoing considerations of the Chalmers study the following strong and weak aspects can be given (see Table 9):

Table 10 Strengths and weaknesses of data collection and quality in the Chalmers studies[18], [20].

DQI	Strengths	Weaknesses
Quantitative	In the data collection process variation within given quantities could be given.	No quantitative data quality indicators have been given although some knowledge on the data distribution may have been known.
Qualitative	Data quality requirements have been formulated in main report; Time coverage and geographical coverage as part of data questionnaire.	Only for precision, completeness, representativeness and uncertainty a quality check has been made explicit. For the other requirements, like time or technology coverage no indication has been given.

It appears that in the Chalmers study the ambitions were quite high considering the quality of the data to be used. During the process the ambition level had to be lowered. The effect of this is also clear from the evaluation (see Table 10) based on the data quality indicators proposed by TNO (see 2.6). A number of crucial fields (valid time span, area, type of average, et cetera) are lacking from the process sheets given in the report. This makes it hard to establish the data quality for a number of data quality indicators (see Table 10).

From the evaluation it appears that the Chalmers study scores low on most indicators. This is partly due because the necessary data for assessing the DQIs are missing in the reports.

Table 11 Evaluation of the Chalmers study based on the seven proposed data quality indicators.

Data Quality Indicator	Chalmers	Score [1)]
Time-related coverage	Valid time span is not indicated. Sources stem from 1981 – 1997. Deviation from 1998 is not mentioned specifically.	5
Geographical coverage	Area is sporadically indicated. Deviation from Denmark is not mentioned specifically.	5
Technology coverage	Technology not specifically mentioned. Deviation from average technology is not given.	5
Precision, completeness and representativeness of the data	Indicated in terms medium, fair, good in relation to common LCA practice. For steel can see Table 13	5
Consistency and reproducibility of the methods used	Method for data collection is only sporadically mentioned. No reproduction of method possible. It is possible that in some cases the method is reproducible from mentioned literature. No indication of reproducibility has been given.	5
Data sources and their representativeness	Data sources have been given, but without indication of representativity. Some sources are personal communications.	2, 4, 5
Uncertainty of the information	In case a value is an average its mean has been given, however the use of standard deviation or another indicator of the variability has not been given. The occurrence of known data gaps is mentioned. The uncertainty has been described in terms of small, medium large.	5

1 The meaning of the value can be found in the pedigree matrices given in Appendix.

3.2.2 Packaging steel

For the process sheet describing the manufacturing of packaging steel an analysis of the strengths and weaknesses has been made according to the data quality requirements used for the evaluation in the Prognos study of the same process [17].

Table 12 Strength and weakness analysis for the manufacturing of packaging steel in the Chalmers study[18].

DQI	Strengths	Weaknesses
Coverage	Qualitative assessment of representativity (see)	Assumption (as data are obtained from APEAL) that average technology is given
Type of average		Unknown
Data gaps	No data gaps known in inventory analysis	Data gaps known in steel production (additives, landfill of waste)
Scope of the process	Scope of the process is given for aggregated processes	
Allocation	Allocation of avoided production of pig iron	

A data quality assessment was part of the Chalmers study for the most significant processes (only qualitative estimation). As an example the assessment of data quality for the significantly contributing processes for the steel cans from [20] is shown in Table 13.

Table 13 Assessment of data quality for the most significant processes for the steel can system [20].

Process	Uncertainty	Completeness	Representativity
Steel can production	Medium	Fair	Fair
Transport of iron to tinplate production	Medium	Good	Fair
Primary aluminium production	Medium	Good	Fair
Distribution of beverage	Medium	Good	Good
Avoided steel production	Medium	Good	Fair

In the representativity the representation of the specific industry, the time-related, geographical and technological representativity of the data are reflected [20]. The quantitative evaluation is related to what is common in LCAs. This of course leads to the introduction of more subjectivity.

3.3 Conclusions concerning data quality in the Chalmers and Prognos studies

From a Strengths and Weaknesses analysis of both the Prognos as the Chalmers study, it becomes clear that both studies had the intention to integrate data quality into the process. From the data requirements given in the Chalmers study it is obvious that this study had the highest ambitions.

The high ambition level for the Chalmers study could not prevent that this study scores low on the following data quality indicators:
- Time-related coverage;
- Geographical coverage;
- Technology coverage;
- Precision, completeness and representativeness of the data;
- Consistency and reproducibility of the methods used;
- Data sources and their representativeness;
- Uncertainty of the information.

The low performance is mainly due to the absence of data needed to assess the status for a given data quality indicator. Besides, a clear evaluation, of in particular the coverage of the data, is lacking form the report.

The Prognos study has a better performance, though for a number of indicators (e.g. precision, completeness and representativeness of the data or uncertainty of the information) the data needed to assess the data quality are absent.

Under the scope of our study it was not possible to verify the LCI data used in the Prognos or Chalmers study. We can thus not formulate a conclusion on the quality of the LCI data (completeness of emissions, use of raw materials, correctness of values) themselves.

4. Overall conclusions and recommendations

4.1 Overall conclusions

From the review of data quality and from the evaluation of two important LCA studies related to beverage-packaging systems the following conclusions can be drawn:

- Data quality is more and more becoming an issue in the field of LCI and LCA. Insufficient data quality is the most commonly reported problem related to data uncertainty in LCAs. The concept of data quality has however not been clearly defined up to this moment;
- ISO has made the following data quality requirements part of the ISO 14040 standard:
  - Time-related coverage;
  - Geographical coverage;
  - Technology coverage;
  - Precision, completeness and representativeness of the data;
  - Consistency and reproducibility of the methods used;
  - Data sources and their representativeness;
  - Uncertainty of the information.
- The formulation of data quality requirements must be related to the goal and scope of either the LCI study or the LCA study;
- Uncertainty in the LCI and other data used in LCAs has an important impact on the final results of a study and has major implications for the significance of observed differences between the systems that have been compared;
- Though uncertainty analysis is seen as an important instrument to deal with data uncertainty in LCI, its application is still in its infancy;
- Data certification is a way to insure a standard data quality level. Data certification has however not yet been applied to LCI or LCA data;
- The German Prognos study has in general good scores on data quality for the time-related and the geographical coverage. Also the representativeness of the data sources scores well;
- Relevant data descriptions needed to assess the score for other data quality indicators (technology coverage, precision, completeness, representativeness, consistency and reproducibility of the methods and data uncertainty) are generally missing from the Prognos study and as a result the study scores low;
- The Danish Chalmers study had the ambition to set a high standard for data quality. Despite this ambition the study scores low on many data quality indicators (coverage, precision, completeness, representativeness, consistency and reproducibility of the methods, data sources and data uncertainty);
- The weakness, shown in the data quality of the two studies, makes it difficult to use the results for policy purposes;

- The peer review of LCAs is one of the ways to increase the quality of an LCA. However, within these reviews there is normally no in-depth data verification as this requires a far greater effort than is commonly made;
- Increasing the quality of LCI and LCA data will increase the reliability of LCA results and improve the quality of this instrument by ensuring full transparency of data and models used.

4.2 Recommendations to APEAL

From the above-mentioned conclusions the following recommendations for APEAL have been distilled:

- Handling data uncertainty should be part of an LCI or LCA. Performing stochastic modelling is a promising technique to handle data uncertainty;
- The quality of data has to be ensured by a process of reviewing and verification;
- The following data quality indicators must be part of an LCI data certification procedure:
  - Time-related coverage;
  - Geographical coverage;
  - Technology coverage;
  - Precision, completeness and representativeness of the data;
  - Consistency and reproducibility of the methods used;
  - Data sources and their representativeness;
  - Uncertainty of the information.
- A data certification procedure has to be implemented to guarantee a certain data quality level and a guideline should deal with the occurrence of low quality data.
- A procedure must be developed to describe how to handle the case of low quality data, as well as the case of differences between the levels of quality of the different data. Important aspects of the procedure will be:
  - Check of the completeness/reality of the model that simulates the chain to be analyzed (input, output, process descriptions, boundaries);
  - Check of the reliability/quality of the (used) data;
  - Check of the mass/energy balances of the observed (production) processes.
- A balanced application of certified data in combination with a sensitivity analysis will strongly improve the outcome of an LCA analysis.
- Two key aspects are important to get the procedure running:
  - A system has to be introduced in order to get industrial sectors to deliver the LCI data of their processes. The quality of these data has to be assessed by a certification bureau. Dependent of the outcome of this assessment a certification body will issue a certificate for the overview of the process data.

– The certification procedure has to become a part of the ISO 14040 series. A discussion with the ISO bureau has to be started to realize such an inclusion.

Even when a data certification procedure and a sensitively analysis complete LCA studies, the results impact has to be combined with the outcome of economic and social analyses with regard to policy making. It is recommended to integrate environmental, economic and social analyses for society relevant studies.

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Appendix 1 Pedigree matrices

Score	Temporal correlation	Geographical correlation	Technological (process) correlation	Represen-tativeness of the data	Consistency and reproducibility of the methods used	Data sources and their repre-sentativeness	Uncertainty of the information
1	Less than 3 years of difference to year of study	Data from area under study	Data from enterprises processes and materials under study	Very high	Very high	Data from reviewed source	Data with a coefficient of variation (c.v.) below 10%
2	Less than 6 years diffe-rence	Average data from larger area in which the area under study is included	Data from processes and materials under study but from different enterprises	High	High	Data from public written source (not reviewed)	Data with a c.v. 10 to 25%
3	Less than 10 years difference	Data from area with similar production conditions	Data from processes and materials under study but from different technology	Moderate	Moderate	Data from closed written source (not reviewed)	Data with a c.v. 25 to 50%
4	Less than 15 years difference	Data from area with slightly similar production conditions	Data on related processes or materials but from same technology	Low	Low	Other sources	Data with a c.v. 50 to 100%
5	Age of data unknown or more than 15 years of difference	Data from unknown area or area with very different production conditions	Data on related processes or materials but from different technology	Very low or unknown	Very low or unknown	Unknown source	Data with a c.v. over 100% or unknown c.v.