TECHNISCHE UNIVERSITÄT DRESDEN

Fakultät Wirtschaftswissenschaften

DRESDNER BEITRÄGE ZUR LEHRE DER BETRIEBLICHEN UMWELTÖKONOMIE

Nr. 57/2012

Günther, E. / Scheel, R. / Nürnberg, A. (Hrsg.)

The differentiation between variability uncertainty and knowledge uncertainty in life cycle assessment

A product carbon footprint of bath powder "Blaue Traube"

Budzinski, M.

Herausgeber:

Lehrstuhl für
Betriebswirtschaftslehre
Betriebliche Umweltökonomie

ISSN 1611-9185

Prof. Dr. Edeltraud Günther
Dipl.-Vw. Ramona Scheel
Dipl.-Kfm. Andre Nürnberg
Maik Budzinski

Technische Universität Dresden
Fakultät Wirtschaftswissenschaften
Lehrstuhl für Betriebswirtschaftslehre,
insbes. Betriebliche Umweltökonomie
01062 Dresden

Telefon: (0351) 463-3 4313
Telefax: (0351) 463-3 7764

E-Mail: bu@mailbox.tu-dresden.de
Homepage: www.tu-dresden.de/wwbwlbu

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Diplomarbeit eingereicht: 2012
Veröffentlicht: 2012

Foreword

Due to the emergence of shortages concerning natural resources and the globalization of production, sustainability has become vital in business decisions. Meanwhile, sustainability management has become an independent field of research in business science and in the decision processes of companies. The research and teaching of the Chair of Environmental Management and Accounting of the Technische Universität Dresden focus on the economic and environmental efficiency (e^3) in organizations. Strategies for practical use are developed based on scientific concepts. In recent years the importance of the natural environment in the economic sciences has been increasing continuously.

The research program of the Chair of Environmental Management and Accounting at the Technische Universität Dresden is reflected in the composition of the teachings. In this way the knowledge gained from the theoretical and practical research flows directly into each of the lectures. The current scientific series "Dresdner Beiträge zur Lehre der Betrieblichen Umweltökonomie" aims to support this integration process. Contents of the scientific series are predominantly theses selected from the Chair of Environmental Management and Accounting through which the reader may gain an insight into the key activities of the chair as well as a clear understanding of the work content.

The scientific series was composed by Dr. Susann Silbermann and the coordination of the present series was carried out by Dipl.-Kffr. Kristin Stechemesser.

The following thesis deals with methods to increase the reliability of the results in life cycle assessment. The paper is divided into two parts. The first part points out the typologies and sources of uncertainty in LCA and summarises the existing methods dealing with it. The methods are critically discussed and pros and cons are contrasted. Within the second part a case study is carried out. This study calculates the carbon footprint of a cosmetic product of Li-iL GmbH. Thereby the whole life cycle of the powder bath Blaue Traube is analysed. To increase the reliability of the result a procedure, derived from the first part, is applied. Recommendations to enhance the product´s sustainability are then given to the decision-makers of the company. Finally the applied procedure for dealing with uncertainty in LCAs is evaluated.

The aims of the thesis are to make a contribution to the understanding of uncertainty in life cycle assessment and to deal with it in a more consistent manner. As well, the carbon footprint of the powder bath shall be based on appropriate assumptions and shall consider occurring uncertainties.

Basing on discussed problems, a method is introduced to avoid the problematic merging of variability uncertainty and data uncertainty to generate probability distributions. The introduced uncertainty importance analysis allows a consistent differentiation of these types of uncertainty. Furthermore an assessment of the used data of LCA studies is possible.

The method is applied at a PCF study of the bath powder Blaue Traube of Li-iL GmbH. Thereby the analysis is carried out over the whole life cycle (cradle-to-grave) as well as cradle-to-gate. The study gives a practical example to the company determining the carbon footprint of products. In addition, it meets the requirements of ISO guidelines of publishing the study and comparing it with other products.

Within the PCF study the introduced method allows a differentiation of variability uncertainty and knowledge uncertainty. The included uncertainty importance analysis supports the assessment of each aggregated unit process within the analysed product system. Finally this analysis can provide a basis to collect additional, more reliable or uncertain data for critical processes.

Edeltraud Günther

The scientific foundation of the work is based upon the results of the diploma thesis by Maik Budzinski which was written at the TU Dresden, Chair of Environmental Management and Accounting.
Professor/Lecturer: Prof. Dr. Edeltraud Günther / Supervisor: Dipl.-Vw. Ramona Scheel and Dipl.-Kfm. Andre Nürnberg. The author is solely responsible for the content of this scientific work.

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List of abbreviations

BT	Blaue Traube
c	specific heat capacity of water
CTV	contribution to variance
CV	coefficient of variation
CO_2	carbon dioxide
CO_2-e	carbon dioxide equivalent
DQG	data quality goal
DQI	data quality indicator
E	energy
g	gram
GWP	global warming potential
H_2	hydrogen
H_2O	water
HCl	hydrogen chloride
K	Kelvin
kg	kilogram
km	kilometre
kWh	kilowatt hour
LCA	life cycle assessment
LCI	life cycle inventory
m	mass
O_2	oxygen
p	probability
Q	quantile
RS	relative sensitivity
SD	standard deviation
SDg95	square of geometric standard deviation
SiC_{14}	silica tetrachloride
SiO_2	silica dioxide

1 Introduction

"Scientific knowledge is a body of statements of varying degree of certainty – some most unsure, some nearly sure, but none absolutely certain."[1]

Richard P. Feynman

Nobel laureate in physics Richard P. Feynman point out the general circumstances of science within a speech at the congress of the National Academy of Science in autumn 1955. Every measurement, data and scientific conclusion is connected with a specific degree of uncertainty. No scientific fact is detached by uncertainty.

And even if it is justified to assume, that a scientific fact is (nearly) certain, other challenges occur when modelling systems, which shall represent the nature. The essential characteristic of a model is to simplify nature. It is intended to generalise things. Otherwise we would have to follow every detail to its origin and we will never be done to make a statement.

That is the foundation of life cycle assessment (LCA). LCA as a tool for environmental decision-making is based on scientific facts and is, moreover, a data intensive procedure. It must regard uncertainty to increase the reliability of its results. Otherwise inappropriate activities or forbearance might result from the given recommendations.

The aims within LCA are simplifying nature and holding the degree of uncertainty on a low level. Therefore several methods are available, each with specific pros and cons. The challenge is to use these methods in an appropriate manner to say that the LCA model is manageable, but valid.

The following thesis deals with methods to increase the reliability of the results in Life Cycle Assessment. The paper is divided into two parts. The first part (chapters 2 and 3) points out the typologies and sources of uncertainty in LCA and summarises the existing methods dealing with it. The methods are critically discussed and pros and cons are contrasted. Within the second part (chapters 4 and 5) a case study is carried out. This study calculates the carbon footprint of a cosmetic product of Li-iL GmbH. Thereby the whole life cycle of the powder bath Blaue Traube is analysed. To increase the reliability of the result a procedure derived from the first part is applied. Recommendations to enhance the product´s sustainability are then given to the decision-makers of the company. Finally the applied procedure for dealing with uncertainty in LCAs is evaluated.

The aims of the thesis are to make a contribution to the understanding of uncertainty in life cycle assessment and to deal with it in a more consistent manner. As well, the carbon footprint of the powder bath shall be based on appropriate assumptions and shall consider occurring uncertainties.

1 FEYNMAN, G.; LEIGHTON, R. (Ed.) (1998), p. 233

The proceeding of the thesis is illustrated in the following figure.

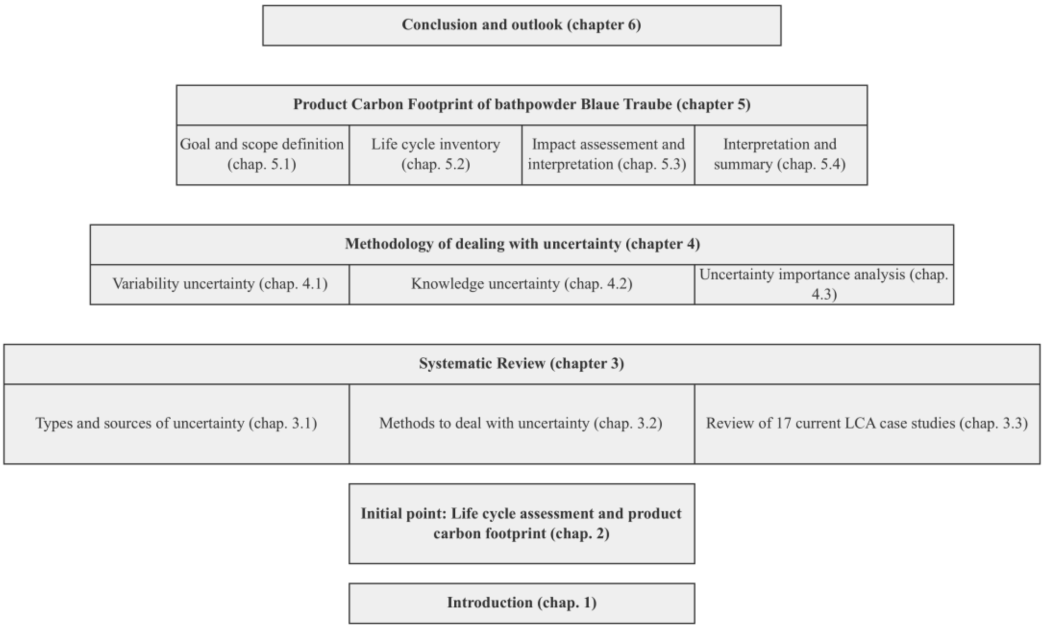

Figure 1: Proceeding of the thesis
(Own illustration.)

The foundation of this thesis is the systematic review (chapter 3). Basing on the reviewed literature, a methodology is derived to deal with uncertainties in LCA (chapter 4). The procedure is than applied within the PCF study (Chapter 5) and is finally discussed in chapter 6.

2 Life cycle assessment and product carbon footprint

The following chapter explains the general procedure of LCA. Also the relation to PCF as a specific part of LCA shall be identified.

Life cycle assessment is a technique to determine the environmental impact of a product or service. It can assist in identifying opportunities to improve the environmental performance of products; informing decision-makers in industry, government or non-government organizations; the selection of relevant indicators of environmental performance; and marketing activities.[2]

According to the European Standards ISO 14040[3] and ISO 14044[4] LCA studies include four phases.

1) The goal and scope definition
2) Inventory analysis
3) Impact assessment, and
4) Interpretation

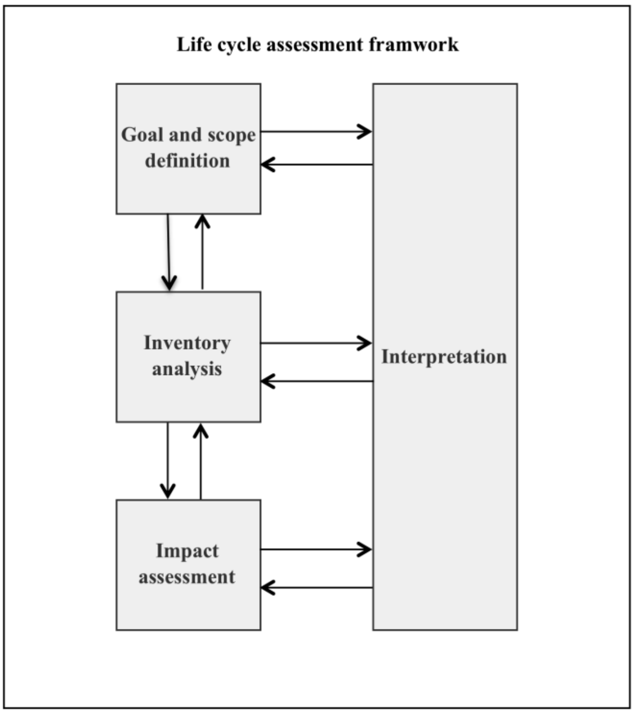

Figure 2: Phases of life cycle assessment
(According to ISO 14040)

Within the *goal and scope definition* the intended application and the reasons for carrying out an LCA study are examined. As well, the scope of the study should be defined sufficiently.

2 Cf. NAGUS (Ed.) (2006a), p. 4
3 NAGUS (Ed.) (2006a)
4 NAGUS (Ed.) (2006b)

The analysed product system with the system boundary and the functional unit is to be explained in this phase too. Generally the whole life cycle of the product should be analysed. The functional unit represents the quantified performance of a product system and is used as a reference unit, to which all determined impacts refer.

Life cycle inventory analysis includes data collection and calculation procedures quantifying the relevant inputs and outputs according to the functional unit. Within this phase the input and output data is collected for all unit processes, which represent the analysed product system. Inputs illustrate product, material or energy flows that enter a unit process. Outputs leave a unit process. The several unit processes are connected and model the product system (figure 3).

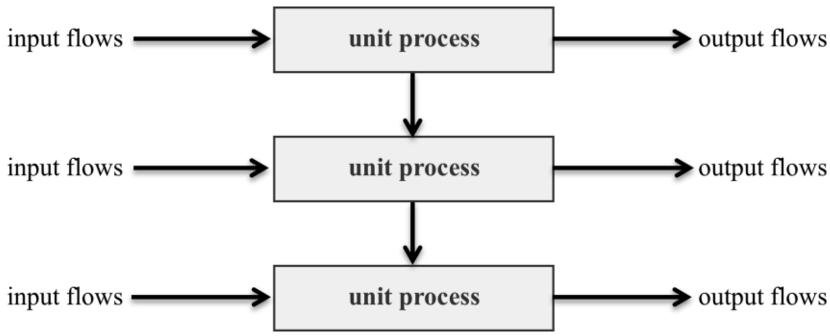

Figure 3: Connection of unit processes
(According to ISO 14040)

Closely connected to the unit processes are elementary flows. These flows leave the analysed product system and are of vital importance. Elementary flows are materials, products or emissions leaving the system into environment without human transformation. That means, these flows determine the environmental impact.

The third phase *impact assessment* takes the results of the inventory analysis and relates its potentially environmental impact. This is achieved by classifying the LCI results, i.e. emissions into impact categories and thereafter by calculating the results using category indicators.

The *interpretation* is carried out according to the goals and scope of the study. It should deliver conclusions, explain limitations and provide recommendations to decision-makers.

An environmental impact category is e.g. the product carbon footprint (PCF). PCF is defined as the sum of emissions effecting climate change within the life cycle of a product. It is denoted in kg carbon dioxide-equivalent. CO_2-eq is a relative measure for describing how much a certain amount of greenhouse gas may cause to climate change. It is obtained by multiplying the greenhouse gas emission by its global warming potential (GWP) within a specific time horizon (usually 100 years).[5] The basis of allocating the GWP to the several gases is the im-

[5] Cf. PACHAURI, R.K; REISINGER, A. (Eds.) (2007), p. 36

pact of one kg carbon dioxide (CO_2 get the factor 1). Compared to the potential impact of CO_2 the potentials of other gases are determined. For instance methane gets the factor 25, if the considered time horizon is 100 years. Other greenhouse gases next to carbon dioxide and methane are nitrous gases, hydrofluorocarbons and sulphur hexafluoride.

Considering to the explained procedure, within a PCF study all greenhouse gas emissions shall be detected, which enter or leave the product system. This is carried out in the inventory analysis. Furthermore these gases are weighted by its specific factors (impact assessment). Finally the output emissions are reduced by the input emissions to calculate the total global warming potential of the analysed product.

3 Systematic review

To detect the current state of knowledge according to the treatment of uncertainties in LCA a literature review is carried out.

The review of existing publications, which deal with the treatment of uncertainties in LCA, is the basis of this thesis. The review is performed in the five steps:[6]

1) Problem formulation
2) Data collection
3) Data evaluation
4) Analysis / interpretation
5) Public presentation

The aim of the review is to find out what types and sources of uncertainty within LCA are already identified in literature. Also the methods shall be summarised to treat these uncertainties.

The data collection is carried out by an extensive research in literature databases. The used databases, search strings and the number of found documents are represented in the appendix. Also literature, which is collected pyramid, is considered. Thereby, cited documents of other authors within the found literature are analysed too.

The data evaluation of all documents, which are determined by the research, is arranged by reading the topics and the abstracts of the collected documents. Afterwards, the remaining documents are analysed in-depth.

The interpretation of documents is carried out by using the MAXqda software and MS Excel. When carrying out the analysis, it is possible to adjust the further procedure of this review depending on the intermediate results. This procedure allows to take common thoughts of authors and to follow them in a deeper manner.

Finally the results of the review are presented in the following chapter.

3.1 Types and sources of uncertainty

LCA as a tool for environmental and ecological decision-making includes uncertainty. Ascough II et al. (2008) incorporate four typologies of uncertainty into environmental management and decision-making: knowledge uncertainty, variability uncertainty, linguistic uncertainty and decision uncertainty.[7]

Knowledge uncertainty[8] refers to the limitation of human knowledge, which may be reduced by additional research. It is also known as epistemological uncertainty and includes uncertainties about process understanding, data and parameters as well as uncertainty of the model´s

6 Cf. HART, C. (1998), p. 34
7 Cf. ASCOUGH II, J.C. et al. (2008), pp.386-390
8 Cf. ASCOUGH II, J.C. et al. (2008), pp. 388-389

structure. Data uncertainty arises from measurement errors, caused in the measurement instrument and errors and biases in sampling.

According to Ascough et al. *variability uncertainty*[9] is related to the inherent variability in natural and human systems and cannot be reduced by additional investigations. Natural variability refers to the inherent randomness of nature. The uncertainty associated with human input can have a significant impact at all stages of environmental decision-making, but has limited attention in literature.

Despite the definition by Ascough et al. as an irreducible phenomena of nature, it should be mentioned, that variability uncertainty only results because of the simplification of nature. This simplification can be carried out temporal, spatial or in object groups. If scientists would be able to detect every single case with its causes and effects, no variability uncertainty would exist. Hence, variability uncertainty is as well reducible. It only results from simplification of the real world, which is generally helpful, especially to draw conclusions.

Linguistic uncertainty[10] arises because of vague, ambiguous and context dependent attributes of human language. Natural and scientific language sometimes allows cases where a precise description of a subject is not available. This type of uncertainty results in misinterpretation of results and inappropriate use of scientific methods.

Decision-making uncertainty[11] arises whenever there is a controversy about how to quantify and compare social objectives. It is related how model predictions are interpreted and communicated. When uncertainty is not properly explained or understood, the given recommendations may cause in inappropriate actions. The three types knowledge uncertainty, variability uncertainty and linguistic uncertainty result in decision uncertainty (figure 4).

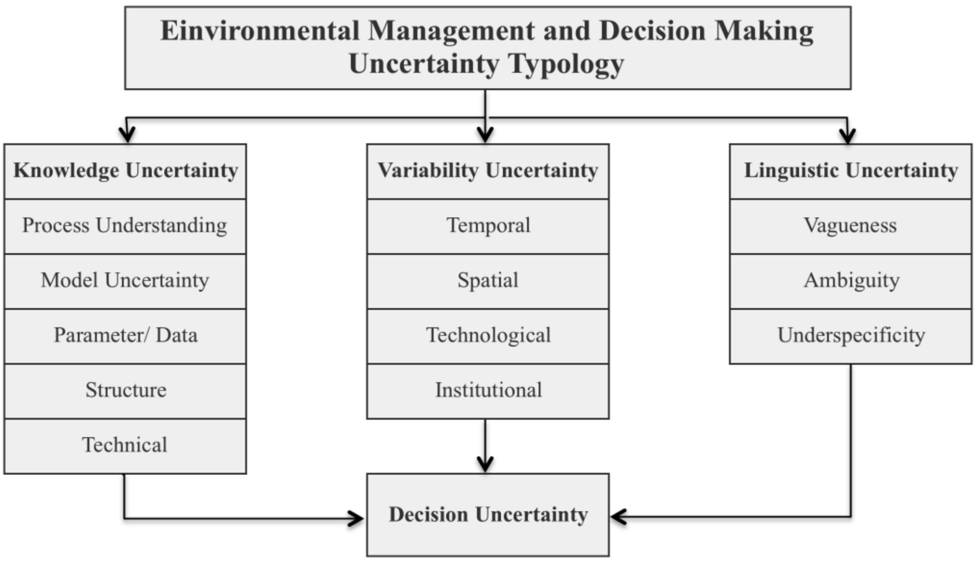

Figure 4: Uncertainty typology in environmental management and decision-making
(Source: ASCOUGH II, J.C et al.(2008))

9 Cf. ASCOUGH II, J.C. et al. (2008), p. 389
10 Cf. ASCOUGH II, J.C. et al. (2008), p. 390
11 Cf. ASCOUGH II, J.C. et al. (2008), pp. 389-390

Several authors have already summarised types and sources of uncertainty in LCA. Especially noteworthy are the studies of Björklund (2002)[12] and Huijbregts (1998)[13]. According to Björklund uncertainty in life cycle assessment arises due to the lack of knowledge about the true value of a quantity. Uncertainty should be distinguished from variability, “which is attributable to the natural heterogeneity of values”.[14] But the effect of variability is equal. The result of an LCA without regarding variability is less reliable.

Performing an LCA on every phase uncertainty can arise. Huijbregts and Björklund summarize the types of uncertainty related to the phases of LCA. The following table illustrates the connection between the definitions of Ascough et al., Huibregts and Björklund.

Table 1: Sorces and types of uncertainty in LCA

Phase		**1) Goal and scope definition**	**2) Inventory analysis**	**3) Impact assessment**			
				Choice of impact categories	Classification	Characterisation	Weighting
Type							
Knowledge uncertainty	*Parameter uncertainty (data inaccuracy, data gaps, unrepresentative data)*		Inaccurate emission measurement, lack of data			Uncertainty in life times of substances, lack of data	Inaccurate normalisation data
	Model uncertainty	Cut-offs	Linear instead of non-linear modelling	Impact categories are not known	Contribution to impact category is not known	Characterization factors are not known	Weighting criteria are not operational
	Uncertainty due to choices	Functional unit, system boundary	Use of several allocation methods	Leaving out known impact categories		Using several characterization methods within one category	Using several weighting methods
Variability uncertainty	*Temporal variability*		Differences in temporal emission inventories			Change of temperature over time	Change of social preferences over time
	Spatial variability		Regional differences in emission inventories			Regional differences in environmental sensitivity	Regional differences in distance to political targets
	Variability between sources/ objects		Differences in emissions between factories which produce the same product			Differences in human characteristics	Differences in individual preferences when using panel method
Linguistic uncertaint	*Estimation of uncertainty*		Estimation of uncertainty of inventory parameters			Estimation of uncertainty of characterization parameters	

(According to ASCOUGH et al (2008),. BJÖRKLUND, A. (2002) and HUIJBREGTS (1998))

12 Cf. BJÖRKLUND, A.E. (2002), pp. 64-72
13 Cf. HUIJBREGTS, M.A.J. (1998), pp. 273-280
14 Cf. BJÖRKLUND, A.E. (2002), p. 64

Knowledge uncertainty can be divided into parameter uncertainty, model uncertainty and uncertainty due to choices.

Parameter uncertainty reflects the incomplete knowledge about the true value of a parameter, e.g. due to imprecise measurements.[15] Parameter uncertainty includes aspects like data inaccuracy, data gaps and unrepresentative data as types of uncertainty. Furthermore, Huijbregts (1998) defines parameter uncertainty as well as an inclusion of variability in data.[16] In contrast, Björklund (2002) explicitly distinguishes between parameter uncertainty and variability. Within this thesis it is evaluated, that the definition of Björklund is more coherent.

Model uncertainty results from assumptions and simplifications of the real world.[17] When modelling the real world it lies in a models nature that many aspects cannot be included. In practice it is difficult to separate this type from others such as parameter uncertainty.[18][19] Also the confusion of model uncertainty to a type of variability uncertainty is possible. Considering the classification of the table, model uncertainty arises, if models are used inaccurately, e.g. without regarding variability uncertainty or mistakes.

Uncertainty due to choices partly overlaps with model uncertainty. Huijbregts (1998) argues that this type of uncertainty arise when defining the functional unit or in the weighting phase. When weighting the results of the impact categories no general agreement exists within literature.[20] The weighting set may be based on political reduction targets, damage costs and panel preferences in reducing environmental impacts.

Variability uncertainty in LCA can be classified into *temporal*, *spatial* and *variability between objects and sources*.[21] [22] All three types reflect the unavoidable variation of the analysed system. The definition of parameter uncertainty by Huijbregts and Björklund may result in overlapping with other types of uncertainty. Especially spatial variability, which represents the inherent fluctuations in the real world, may result in parameter uncertainty, when using the definition of Huijbregts.

According to Björklund even the *estimation of uncertainty* contains uncertainty.[23] This results from the underlying assumptions, which are necessary to deal with it in a mathematical manner. Also the different use of terms (***linguistic uncertainty***) describing the terminology of uncertainty may be a source of this type.

The several sources of uncertainty can be allocated to the phases of LCA. Within the goal and scope definition the choice of the functional unit and system boundary, as well as cut-off errors influence the reliability of the results. The influence of the functional unit are discussed by Matheys et al. (2004) and Ciroth et al. (2008). Matheys et al. find out that the choice of functional unit influences the result of an LCA and results in a kind of uncertainty.[24] The most

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15 Cf. HUIJBREGTS, M.A.J. et al. (2003), p. 2600
16 Cf. HUIJBREGTS, M.A.J. (1998), p. 274
17 Cf. HUIJBREGTS, M.A.J. (2003), p. 2601
18 Cf. DE KONING, A. et al. (2010), p. 81
19 Cf. RÖÖS, E. et al. (2011), p. 340
20 Cf. HUIJBREGTS, M.A.J. (1998), p. 275
21 Cf. HUIJBREGTS, M.A.J. (1998), pp. 275-277
22 Cf. BJÖRKLUND, A.E. (2002), p.65
23 Cf. BJÖRKLUND, A.E. (2002), p. 65
24 Cf. MATHEYS, J. et al. (2004), p. 195

appropriate and widely accepted functional unit should be chosen. To define an appropriate functional unit Ciroth et al. suggest using statistical sampling. The choice of functional unit and hence the system boundary affect the collection of life cycle inventory data and finally the environmental impact results of an LCA. Williams et al. (2009) [25] argue that an uncertain inventory cannot lead to a certain impact assessment and it should get the focused attention of the LCA community.[26] Cut-off errors result on the systemic underestimation of impacts caused by the exclusion of processes within an LCI.[27]

Life cycle inventory (LCI) is a phase in which all types of uncertainty may occur. Furthermore the collected data are the basis of all statements, which are reached according to LCA. Thus LCI requires particular observation.

Within the impact assessment phase a common problem is given by the uncertainty of characterization factors.[28] [29] For instance, the GWPs of greenhouse gases are calculated by physicians. This calculation contains uncertainty too. Also the change of preferences within the weighting of results should be mentioned. This quite subjective evaluation is connected with human variability uncertainty.

To summarize we can record that there are several sources of uncertainty in LCA, which affect the reliability of its results. The most important sources for LCA practitioners are the choice of the functional unit, all sources within the LCI phase (i.e. sources of variability uncertainty) and the uncertainty of emission factors. The choice of functional unit influences directly the collected data and hence the inventory. If the functional unit is chosen inappropriately, the collected data will not describe the real world correctly. Furthermore if potential variations in collected data and data quality aspects are not regarded, the results of LCA could be not valid.

In LCA, distinguishing between the explained types of uncertainty is not easy, but should be attempted to understand uncertainty and to deal with it in a consistent manner. Thus, the differentiation of variability uncertainty and knowledge uncertainty is the matter of this thesis.

Furthermore in this thesis parameter uncertainty is explicit distinguished from variability uncertainty. Parameter uncertainty only refers to data gaps, unrepresentative data and data inaccuracy. In contrast to Huijbregts (1998)[30] it should not be treated by the use of probability theories, e.g. Monte Carlo simulation.

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25 Cf. WILLIAMS, E.D. et al. (2009), p. 934
26 Cf. WILLIAMS, E.D. et al. (2009), p. 930
27 Cf. WILLIAMS, E.D. (2009), p. 935
28 Cf. CELLURA, M. et al. (2011), p. 4703
29 Cf. SUH, Y.-J.; ROUSSEAUX, P. (2002), p. 197
30 Cf. HUIJBREGTS, M.A.J. (1998), p. 274

3.2 Methods to deal with uncertainty

Within LCA literature there exist several approaches, which test the robustness of the results and which increase the reliability of the LCA study. According to Baumann and Tillman (2004) the methods can be summarized into six types.[31]

- Completeness check
- Consistency check
- Sensitivity analysis
- Scenario analysis
- Data quality assessment
- Uncertainty analysis

Completeness and consistency checks can be seen as fundamental points when performing life cycle assessment. They are required to improve all calculation procedures according to data collection and the appropriate modelling within the LCA study. Completeness checks are associated with data gaps and the use of cut-offs. Consistency checks e.g. regard to allocation procedure and the manner of dealing with LCA uncertainties. Moreover LCI databases should be used in a consistent manner, especially when comparing different products. To check these aspects and to avoid mistakes, completeness checks and consistency checks can be carried out during or after the study, e.g. by external reviews.

The methods of uncertainty, sensitivity and scenario analyses as well as data quality assessment are explained in more detail.

3.2.1 Sensitivity analysis

The most common approach in LCA seems to be sensitivity analysis. This analysis determines the effect of changes in one independent parameter on a dependent parameter. According to ISO 14044 a sensitivity analysis should be applied to determine the influence on variations in assumptions, methods and data.[32] An advantage of this method is that it is possible to determine the change of a parameter according to the significant change of the result. Further this analysis can deal with uncertain data without additional, extensive data collection determining the range of data.[33] In literature there exist several definitions of methods, which are based on the procedure of sensitivity analysis. Sometimes the term perturbation analysis[34][35] is used to identify sensitive parameters, which contribute by a small change to a large change in a selected result. Furthermore sensitivity analysis can be used to analyse the influence of nearly every assumption within LCA. The influence of cut-offs as well as assumptions about different possible recycling processes can be investigated with this analysis.[36]

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31 Cf. BAUMANN, H. ;TILLMAN, A.-M. (2004), p. 197
32 Cf. NAGUS (Ed.) (2006b), pp. 75-76
33 Cf. BAUMANN, H. ;TILLMAN, A.-M (2004), p. 199
34 Cf. HEIJUNGS, R.; KLEIJN, R. (2001), p. 143
35 Cf. GUINEE, J.B. (Ed.) (2002), pp. 638-639
36 Cf. MARTINEZ, E. et al. (2010), pp.2295-2299

3.2.2 Scenario analysis

A special type of improving sensitivity is scenario analysis.[37] Scenarios in LCA studies are based on specific assumptions about the future.[38] The analysis determines the effect of variation of several parameters. Thereby scenarios are constructed, which include realistic combinations of parameters. By the use of scenario analysis, specific assumptions about the future, based on the choice of system boundaries, allocation methods, technology, time, space, characterisation methods and weighting methods, can be examined.[39]

3.2.3 Data quality assessment

Increasing the reliability of LCA results the standards of ISO 14044 have certain requirements on the used data. These requirements should be considered in every study. In addition to it, in case of publishing comparative studies, the following aspects must be addressed:[40]

- Age of data and the period over which data should be collected;
- Geographical area from which data should be collected;
- Technology coverage;
- Variability of data;
- Completeness of data;
- Representativeness of data;
- Consistency of the used methodology;
- Reproducibility of the results of the study;
- Sources of data.

Especially the qualitative requirements on data- geographical area, technology coverage, completeness, representativeness and age of data need a systematic assessment. Without such an assessment there is no adequate basis for the judgement of data.[41]

A systematic method is given by Weidema and Wesneas (1996)[42]. They introduced ***data quality indicators (DQI)*** to describe the collected inventory data. These data quality indicators are reliability, completeness, temporal correlation, geographical correlation and further technological correlation (table 2). The analysed LCI data get a score for each indicator, taken from the pedigree matrix. A score of 1 allows the conclusion, that the used data is perfect, according to the respective indicator.

37 Cf. BJÖRKLUND, A.E. (2002), pp. 66-68
38 Cf. BJÖRKLUND, A.E. (2002), p. 67
39 Cf. BJÖRKLUND, A.E. (2002), p. 67
40 Cf. NAGUS (Ed.) (2006b), p. 21
41 Cf. MAY, J.R.; BRENNAN, D.J. (2003), p. 215
42 Cf. WEIDEMA, B.P.; WESNAES, M.S. (1996), pp. 176-174

Table 2: Pedigree matrix

Indicator score	**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 (e.g. by 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
Dependent on the goal and scope of the study (DQG):					
Temporal correlation	Less than three years of difference to year of study	Less than six 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 production conditions	Data from area with slightly similar production conditions	Data from unknown area with very different production conditions
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study but from different enterprises	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

(Source: WEIDEMA, B.P; WESNAES, M.S. (1996))

To specify the desirable characteristics of the data needed for the study it is possible to define ***data quality goals (DQG)*** during the goal and scope definition.[43] The goals shall correspond the requirements of ISO 14044. Furthermore the defined goals can be used to allocate the indicator scores for temporal, geographical and further technological correlation within the pedigree matrix.

In addition to the introduced methods, a ***critical review*** can be carried out subsequently or collaterally to the study. It ensures the scientific and technical validity, appropriate use of data, sound interpretation, transparent and consistent reporting.[44]

3.2.4 Uncertainty analysis

Uncertainty analysis deals with the effect of uncertain data on the overall result of the study.[45] The principle is the use of intervals within the parameters range.

In general, uncertainty analysis in LCA deals with variability uncertainty. In contrast to uncertainty analysis in physics, the object within LCA is not the uncertainty in a measurement, but rather the variability of a countable population. Thus, the examination object is the resulting variability, which is caused by the simplification of nature. The used word in literature may be

43 Cf. BJÖRKLUND, A.E. (2002), p. 66
44 Cf. BJÖRKLUND, A.E. (2002), p.66
45 Cf. BAUMANN, H.; TILLMAN, A.-M. (2004), p. 198

confusing. Expressed with the terms of this thesis, a potential of linguistic uncertainty may arise. Some authors use the word *error* when talking about uncertainty or, more precise, when talking about variability uncertainty. Whether the word error might be misleading, within the following part this term is used and explained.

Ciroth (2004) describes the 'uncertainty problem' in LCA by three sub-problems:[46]

1) Assessing errors (variability uncertainties) in input data;
2) Assessing the propagation of errors (variability uncertainties) in the calculation;
3) Assessing errors (variability uncertainties) in the calculation`s outcome.

Uncertainty analysis deals with all of these three sub-problems. Understanding the existing methods in LCA, it is helpful to review the concept of errors (uncertainty) within error propagation. It is distinguished between systematic and random errors. A systematic error is the deviation of the true value from the expected value. It is characterised by a certain deviation (either + or -), which is avoidable by further investigation. Systematic errors can also be called bias or mistakes. Hence a systematic error is not uncertainty in a statistical or random manner.[47] In contrast, a random error is the deviation of a measured value from its expected value. The deviation is random and differs in its unknown algebraic sign (±). The total deviation of an observed value from its true value is the additive connection of the systematic and random part.

According to the introduced types of uncertainty, systematic errors can be explained as a type of knowledge uncertainty. Random errors are a type of variability uncertainty.

Ciroth (2001) give examples for systematic and random errors in LCA. Systematic errors could be: [48]

- Software with biased counting algorithms;
- Systematic exclusion of substances or processes;
- Measurement errors and errors of calibration;
- Use of unrepresentative data.

Random errors could be:

- Literal errors within data entry;
- Variations within processes;
- Truncation errors.

The differentiation between systematic or random errors of LCA is difficult.[49] However it should be an aim of uncertainty analysis to distinguish between these types. If a systematic error is included, e.g. by the exclusion of processes (algebraic sign is -), the calculated value is always less than the true value. 'Real' variability uncertainty only exists if the possibility is given for both algebraic signs. And this is the proper object of error propagation.

46 Cf. CIROTH, A. et al. (2004), p. 217
47 Cf. DROSG, M. (2006), p. 18
48 Cf. CIROTH, A. (2001), p. 21
49 Cf. CIROTH, A. (2001), p. 22

According to the general distinction between variability uncertainty and other types of uncertainty in LCA the propagation of random errors hence could be interpreted as the propagation of irreducible variability uncertainty. A bias, mistake or systematic error is part of the knowledge uncertainty, i.e. parameter uncertainty.

3.2.4.1 Assessing uncertainty in input data

In contrast to sensitivity analysis, the uncertainty analysis requires extended information about the used data. Before assessing the uncertainty propagation within the analysis the intervals, respectively the probability distribution of each parameter has to be determined. This is possible either by doing further assumptions or by using additional statistical approaches, which is obviously the preferred manner.

If the data basis is sufficient ***statistical analysis*** can be used to determine the mean of the amount of a substance and to ensure these values. Especially estimating methodologies and statistical testing methods (non-parametric tests) should be mentioned. Ciroth (2008) introduced statistical sampling to get *empirical estimates* for the functional unit (weight of yoghurt cups).[50] In contrast to parametrical tests, which are not common in LCA, *non-parametrical tests* do not need the knowledge about the population. With these tests it is possible to describe the population on the basis of the sample size values. Hence they can be used to determine the probability distributions for error propagation. Three statistical tests within LCA[51] shall be mentioned, the Chi-square goodness-of-fit test, Kolmogorov-Smirnov test and Anderson-Darling test. A type of Kolmogorov-Smirnov test is the Lilliefors test, which is used for testing for normal distribution. The Chi-square goodness-of-fit test can be used if the sample is sufficient (> 30), the Kolmogorov-Smirnov test is applicable to samples with less than 30 values.[52] The Anderson-Darling test is designed specific for normal and lognormal distributions.

A general problem of LCA is the data extensive characteristic of this technique. To deal with it some procedures have been developed. One option is to use ***DQIs*** to generate the necessary ranges or distributions. According to May (2003) DQIs can be used to combine this data quality information with numerical approaches.[53] The combined use of data quality indicators has the aim to obtain a cumulative uncertainty value. This value is then the basis for additional uncertainty analysis. The common procedures are described and critically discussed in the following part.

Using DQIs in a qualitative manner, the scores can be interpreted on three levels- data level, process level and system level.[54] Wrisberg use aggregated quality indicators to describe the total system quality according the environmental impact result.[55] Rousseaux et al. propose the comparison of quality performance of each data point/ set to a target quality score.[56] Thereby

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[50] Cf. CIROTH, A.; SROCKA, M. (2008), pp. 265-277
[51] Cf. SANER, D. (2012), p. 5
[52] Cf. LLOYD, S. M.; RIES, R. (2007), pp. 168-169
[53] Cf. MAY, J.R.; BRENNAN, D.J. (2003), pp. 217-218
[54] Cf. MAY, J.R.; BRENNAN, D.J. (2003), p. 217
[55] Cf. MAY, J.R.; BRENNAN, D.J. (2003), p. 217
[56] Cf. ROUSSEAUX, P. et al. (2001), pp. 209-306

the total aggregated quality score of each indicator is determined by the weighted mass contribution of each data point/ set.[57]

To include data quality aspects Weidema and Wesnaes (1996) introduced using DQIs to calculate the modified coefficient of variation (CV) of each LCI data input. The CV is defined as standard deviation divided by the mean.

Equation 3-1

$$CV = \frac{\sigma}{\mu}$$

Within their methodology they distinguish between two sources of uncertainty of data. First the basic uncertainty (variability uncertainty) related to the natural fluctuation and second the additional uncertainty (knowledge uncertainty) related to the quality of data.

The procedure enlarges the natural variability (CV_b) of a data input by taking into account the additional data quality aspects. Additional uncertainty is represented as data quality indicators. The overall uncertainty of each data input (expressed by the modified coefficient of variation) is calculated[58] by the square root of the sum of squares of the individual coefficients.

Equation 3-2

$$CV_{mod.} \coloneqq \sqrt{CV_1^2 + CV_2^2 + CV_3^2 + CV_4^2 + CV_5^2 + CV_b^2}$$

The values of the additional data quality aspects (CV_1 to CV_5) are taken from the following table.

Table 3: Factors of indicator scores I

Indicator score	**1**	**2**	**3**	**4**	**5**
Reliability (CV1)	0	0.03-0.10	0.17-0.25	0.25	0.97
Completeness (CV2)	0	0.00-0.10	?	?	0.25
Temporal correlation (CV3)	0	(For energy use, reduce mean value with:			
		10%	20%	30%	40%)
Geographical correlation (CV4)	0	0.05-0.17	0.10-0.25	0.50	0.50
Further technological correlation (CV5)	0	0.16	0.16	0.33	0.50

(Source: WEIDEMA, B.P.; WESNAES, M.S. (1996))

The incomplete table by Weidema and Wesnaes already contains the idea to reduce the mean for the indicator of temporal correlation. The authors argue that energy efficiency increase

57 Cf. ROUSSEAUX, P. et al. (2001), p. 303
58 Cf. WEIDEMA, B.P.; WESNAES, M.S. (1996), p. 172

gradually. Thus the mean is reduced and an increase is not possible. In contrast to the other indicators, which enlarge the CV.

Frischknecht et al. (2005) developed a similar approach for the ecoinvent database to generate so called uncertainty distributions of input data. Within the database the uncertainty range for each LCI data input is calculated assuming log-normally distributed parameters. The square of the geometric standard deviation is calculated by the following formula[59].

Equation 3-3

$$SD_{g\,95} := \sigma_g^2 = exp\sqrt{[\ln(U_1)]^2 + [\ln(U_2)]^2 + [\ln(U_3)]^2 + [\ln(U_4)]^2 + [\ln(U_5)]^2 + [\ln(U_6)]^2 + [\ln(U_b)]^2}$$

The values of each uncertainty factor (U_1 to U_6) depend, as well, on a pedigree matrix. By means of the pedigree matrix and the allocated scores the uncertainty factors are determined (table 4).

Table 4: Factors of indicator scores II

Indicator score	**1**	**2**	**3**	**4**	**5**
Reliability (U1)	1.00	1.05	1.10	1.20	1.50
Completeness (U2)	1.00	1.02	1.05	1.10	1.20
Temporal correlation (U3)	1.00	1.03	1.10	1.20	1.50
Geographical correlation (U4)	1.00	1.01	1.02	-	1.10
Further technological correlation (U5)	1.00	-	1.20	1.50	2.00
Sample size (U6)	1.00	1.02	1.05	1.10	1.20

(Source: FRISCHKNECHT, R. et al. (2005))

Quite often the natural basic variability (U_b) cannot be calculated, caused by an insufficient sample. Then the basic U is based on expert judgement too.[60]

The square of the geometric standard deviation allows a quick calculation of the 0.025- and 0.975-quantiles of the underlying lognormal distribution. Within the range of the two points 95 % of the values are included.

Equation 3-4

$$Q_{0.025} = \frac{\mu_g}{\sigma_g^2}$$

Equation 3-5

$$Q_{0.975} = \mu_g * \sigma_g^2$$

The approaches of Frischknecht et al. and Weidema/ Wesnaes use data quality information as well as the natural variability, estimated by assumptions or taken from a representative sam-

59 Cf. FRISCHKNECHT, R. et al. (2005), p. 6
60 Cf. WEIDEMA, B.P. et al. (2011), p. 81

ple, to generate a total uncertainty range or respectively the probability distributions. Comparing the approaches, Frischknecht et al. assume that every data quality indicator raises the geometric standard deviation of the underlying lognormal distribution. In contrast Weidema and Wesnaes argue that temporal correlation of energy data does not lead to an increase of uncertainty but in a reduction of the mean, caused by assumed increases of energy efficiency and environmentally friendly technologies over time. All data quality indicators can be interpreted as systematic errors, which reduce the representativeness of used data. It illustrates the main problem of putting data quality aspects into probability distributions. The techniques do not consider the circumstances that systematic errors are not random in statistical manner.

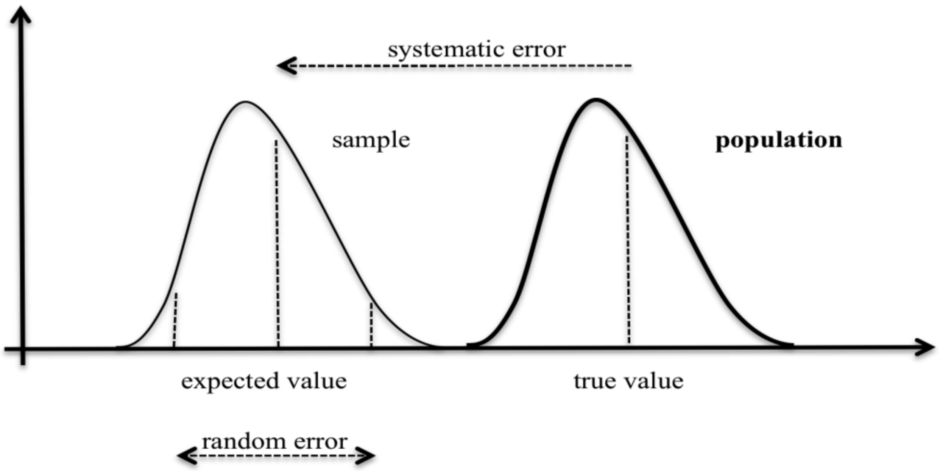

Figure 5: Differentiation between systematic and random errors
(Own illustration.)

The figure with the two lognormal distributions illustrates the difference between systematic and random errors. The fat drawn distribution represents the population and its variability uncertainty. When generating the probability distributions for error propagation, the aim is to display the distribution of the population. But how can it be achieved when mixing systematic and random errors? For instance, it shall be determined the CO_2 emissions of a car per kilometre. Thereby the analysed 100 cars have a mean of 200 g CO_2/ km (expected value) but the population of all cars has a mean of 300 g CO_2/ km (true value). Hence in the example a systematic error occurred during the sampling procedure, caused by e.g. the missing of vans or old vehicles, which have higher fuel consumption. It is obvious that the use of unrepresentative data, lead to an incorrect estimate. In life cycle assessment the use of unrepresentative background data may occur more often than it is desired. The integration of all DQIs into probability distributions is poorly conceived.

Furthermore the procedure does not allow a decomposition of the included data quality aspects and variability uncertainty after the generation of probability distributions.

Thus the approach of Frischknecht within the ecoinvent database is not optimal. It should only be used if only one value of a LCI parameter is available and if it is used in a consistent manner for all parameters within the LCA study.

3.2.4.2 Assessing the propagation of uncertainties

Uncertainty or error propagation can be performed analytical, probabilistic or by fuzzy approach.[61]

The analytical way uses formulas for error propagation, based on *Taylor series expansion*. Taylor series expansions are based on approximation formulas for calculating the variance of a system´s result using stochastic data.[62]

Ciroth (2001) introduced formulas like the Gaussian formula for error propagation or the formula, given by Bader and Baccini to Life Cycle Assessment.[63] Also the outstanding work of Heijungs and Suh (2002)[64], who developed formulas for uncertainty assessment in matrix-based LCAs.

An approach, applying Taylor series expansions to the uncertainty propagation of log-normally distributed parameters, is introduced by Hong et al. (2010).[65]

The equations assume the independency of the several uncertainties of the input parameter. Heijungs (2009) argues that in most cases, no covariance data are available, or the covariance can be assumed to be negligible as the uncertainties are in many cases independent.[66] Analytical approaches for error propagation are not yet implemented in common LCA software tools. However, it is argued implementing Taylor series expansion would be a less time and computationally intensive procedure than Monte Carlo methods.[67] In contrast to Monte Carlo simulation the combination of log-normally and normally distributed parameters is not possible within analytical methods.

The probabilistic way can be performed by *Monte Carlo simulation,* which is the most common[68] method in Life Cycle Assessment. In literature Monte Carlo analysis is often explained as a separate approach within probabilistic simulation.[69] [70] But using this method in LCA, it might be more coherent explaining it as a special case of sensitivity analysis.

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[61] Cf. CIROTH, A. et al. (2004), p.217
[62] Cf. HEIJUNGS, R. (2009), p.514
[63] Cf. CIROTH, A. et al. (2004), p.218
[64] Cf. HEIJUNGS, R.; SUH, S. (2002)
[65] Cf. HONG, J. et al. (2010); p. 499-510
[66] Cf. HEIJUNGS, R. (2009), p. 515
[67] Cf. HEIJUNGS, R. (2009), p. 514
[68] Cf. LLOYD, S. M.; RIES, R (2007), p. 167
[69] Cf. BJÖRKLUND, A.E. (2002) p. 69
[70] Cf. HUIJBREGTS, M.A.J. (1998), p. 277

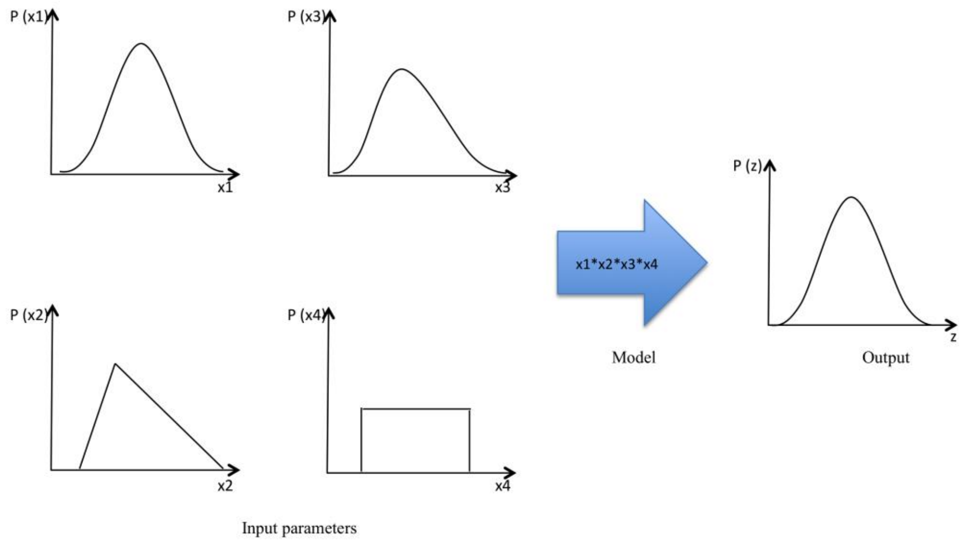

Figure 6: Principle of Monte Carlo simulation in LCA
(Own illustration.)

Figure 6 describes the procedure of Monte Carlo analysis in life cycle assessment. The uncertainty of each input parameter is expressed as a probability distribution. Hence each parameter can vary in a specific range to a certain probability. The most common distributions in LCA are normal, lognormal, uniform and triangular distribution.[71] In a next step random numbers are chosen for each parameter according to the specific probability distribution. These values for each input parameter are chosen and one LCA result is calculated. These steps are repeated usually more than 1000 times to approximate the several probability distributions of input parameter. Hence the LCA result is a probability distribution as well. The advantage of Monte Carlo analysis is that several parameters can be considered and thereby the overall variability uncertainty of the LCA result can be determined. But to perform this analysis the required information of LCI data (which are already quite high) are extended. According to Ciroth (2004) the Monte Carlo Analysis is good for propagation, but the simulation cannot be correct, if the input uncertainties are wrong and it does not tell how to interpret the calculated total uncertainty.[72] Also usual Monte Carlo analysis postulates independency of the included parameters´ uncertainties. Otherwise the correlation should be regarded determining the random numbers either by determining correlation coefficients or by avoiding correlations in modelling the system.

When performing Monte Carlo simulation in life cycle assessment, several authors use the term 'confidence interval'[73][74]. In this thesis this is avoided to reduce linguistic uncertainty. A confidence interval is a stochastic interval, depended by a sample. It is used to indicate the reliability of an estimate.[75] In contrast, when carrying out uncertainty analysis and Monte Carlo

71 Cf. LLOYD, S. M.; RIES, R. (2007), p. 168
72 Cf. CIROTH, A. et al. (2004), p. 217
73 Cf. MILA I CANALS, L. et al. (2010), p. 56
74 Cf. VENKATESH, A. et al. (2011), p. 8185
75 Cf. HUSCHENS, S. (2011), p. 88

simulation in particular, the probability distributions are postulated and hence the parameters of these distributions are (assumed to be) known. And if the distribution is known, it is even possible to calculate a range where 99.99% of the values are included. A more appropriate term describing the probability distributions is 'percentile range'[76] or 'quantile range'.

Currently there is a discussion in LCA community, if using Taylor series expansion instead of Monte Carlo simulation.[77] Taylor series expansion provides similar results while being less time intensive than Monte Carlo simulation.[78]

The fuzzy way calculates the overall uncertainty of the result by using fuzzy numbers. The argument is that fuzziness is more appropriate to model epistemological variability (knowledge uncertainty) that results from different degrees of plausibility or possibility arising from human judgement.[79] Tan (2008) argues, probability is more appropriate to model statistical variability.[80] Hence the main advantage of this theory seems to be the aggregation of interval information about the range within a parameter can be located, and information about the plausibility of its occurrence.

The basic concept is the use of fuzzy sets. In contrast to traditional sets (included or not included), an element can be partly included within fuzzy sets. The degree of belonging of the result is finally described by a membership function (figure 7).

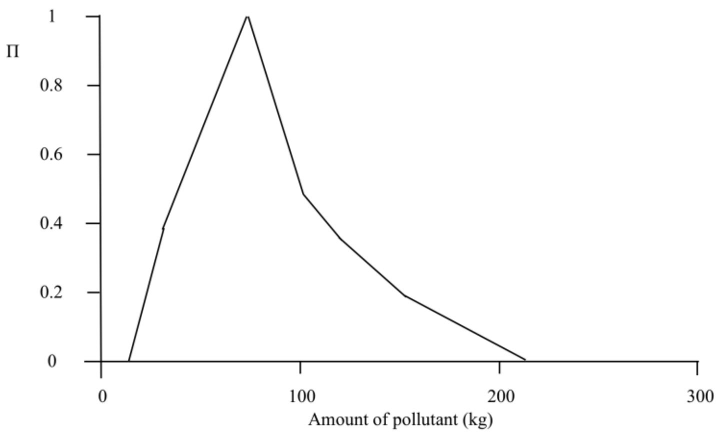

Figure 7: Fuzzy membership function
(Source: TAN, R. et al. (2007))

In a certain way the membership function can be interpreted as a probability distribution, which is the result of Monte Carlo simulation. But the advantage is the extended information about uncertainty. Within the membership function, additional types of uncertainty next to variability uncertainty can be modelled in more appropriate manner.

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76 Cf. RÖÖS, E. (2010), p. 484
77 Cf. WEIDEMA, B.P et al. (2011), p. 84
78 Cf. HONG, J. et al. (2010), p. 500
79 Cf. TAN, R.R. (2008), p.586
80 Cf. TAN, R.R. (2008), p. 586

Besides error propagation fuzzy sets theory can be used in a wide range within life cycle assessment. For instance in the papers of Tan et al. (2007)[81] and Aviso et al. (2011)[82] fuzzy targets are determined for different environmental flows and impact categories. Güereca et al. (2007)[83] proposed fuzzy sets theory to support the decision making process within the evaluation of LCA results. Thereby various scenarios are compared according to its results in different impact categories. The resulted membership function allows the determination of the best scenario.

3.2.4.3 Assessing uncertainty in the calculation´s outcome

A non-trivial question is what to do with the calculated total uncertainty of LCA results? The interpretation of the outcome with inherent uncertainty is not easy. When comparing two or more products it is useful knowing the total variability uncertainty of each product´s impact. In this case the information about the total uncertainty of each outcome provides an adequate comparison. Therefor the uncertainty in each product´s calculation has to be treated in a consistent manner.

When carrying out uncertainty analysis a common way is to indicate the range, within 95 % of the result´s values are located.[84 85 86]

In case when only one product is analysed it might be much harder dealing with the calculated uncertainty range. In this case, supplementary to the calculation of total uncertainty of the result it could be interesting to determine the most significant input parameters contributing to the result´s uncertainty. Therefore additional uncertainty importance analysis is required.

3.2.4.4 Uncertainty importance analysis

Uncertainty importance analysis investigates the influence of an uncertain parameter to the total uncertainty of the result.[87] A parameter can have a large uncertainty, but at the same time this parameter does not contribute significantly to the total uncertainty. Also, it gives more specific information than ordinary sensitivity analysis.[88] Uncertainty importance analysis can be performed in a quantitative, as well as in a qualitative manner.

The quantitative uncertainty importance analysis is performed in the same manner as sensitivity analysis. Within Monte Carlo analysis it might be possible (depending of the software tool, e.g. Crystal Ball) to calculate the uncertainty importance by computing the correlation between parameter uncertainty and model outcome.[89] According to Geisler et al. (2005) the uncertainty importance can be expressed as the contribution to variance (CTV). The contribution of a single uncertain input parameter *i* can be calculated by using the rank-order-

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81 TAN, R. et al. (2007), pp. 1358-1367
82 AVISO, K.B. et al. (2011), pp. 187-196
83 GÜERECA, P. et al. (2007), pp. 488-496
84 RÖÖS, E. et al. (2010), pp. 478-488
85 RÖÖS, E. et al. (2011), pp. 338-350
86 FLYSJÖ, A. et al. (2011), pp. 459-469
87 Cf. BJÖRKLUND, A.E. (2002), p. 67
88 Cf. BJÖRKLUND, A.E. (2002), p. 67
89 Cf. BJÖRKLUND, A.E. (2002), p. 68

correlation coefficient between the parameter *i* and the score of impact category *j*; *n* is the number of parameters contributing to the variance in *j*.[90]

Equation 3-6

$$CTV_{i,j} = r_{i,j}^2 * \left[\sum_{i=1}^{n_i} r_{i,j}^2 \right]^{-1}$$

A further means is to calculate the relative sensitivity (RS), expressed by the ratio of standard deviation σ of a parameter over the critical error Δx (required variation in x to bring about change in the result).[91]

Equation 3-7

$$RS_x = \frac{\sigma_x}{\Delta x}$$

Within the deterministic error propagation Heijungs (2009) uses the term 'key issue analysis' for uncertainty importance analysis. In addition he gives equations for calculating the relative contributions to the variance of the total result within matrix-based LCA.[92]

Qualitative uncertainty importance analysis[93] does not require numerical data as much as in the quantitative manner. Performing the analysis, at first, the most important unit processes are selected (e.g. by contribution analysis). In a second step the data quality indicators of each of these processes are aggregated to a single DQI. Finally the data are brought to a matrix identifying the key parameters.

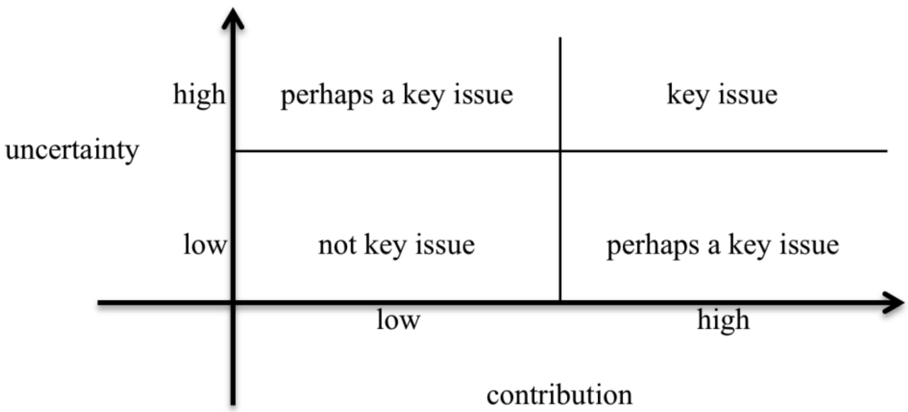

Figure 8: Qualitative uncertainty importance analysis
(Source: BJÖRKLUND, A,E. (2002))

90 Cf. GEISLER, G. et al. (2005), p. 193.3
91 Cf. BJÖRKLUND, A.E. (2002), p. 68
92 Cf. HEIJUNGS, R. (2009), p 516
93 Cf. BJÖRKLUND, A.E. (2002), pp. 67-68

The classification into key issues and not key issues allows a better understanding of model´s input parameters. Hence this analysis can contribute to a reduction of the most important uncertainties by pointing out the rooms of improvement of input parameters. However the analysis does not allow the determination of the total variability uncertainty of the result.

3.2.5 Summary

There exist several types and sources of uncertainty within LCA. And at least the same number of methods seems to be available in literature to deal with these uncertainties. The following table shall summarize the methods, which can be used in the appropriate case. Brackets illustrate the indirect influence of the method to deal with the type of uncertainty. The small x represents the inappropriate usage of DQIs to deal with variability uncertainty.

Table 5: Summary of methods to deal with uncertainty

Typology	Knowledge uncertainty					Variability uncertainty	Linguistic uncertainty
Subtype	Data inaccuracy	Data gaps	Unrepresentative data	Model uncertainty	Uncertainty due to choic-es		Estimation of uncertainty
Completeness check		X		X			
Consistency check	X		X	X	X		X
1) Sensitivity analysis	(X)	(X)	X	X	X	X	
2) Scenario analysis			X	X	X	X	
3) Data Quality Assessment by:							
Data Quality Indicator (DQI)	X		X				
Data Quality Goals (DQG)	X		X				
Critical review		(X)	(X)	(X)	(X)		(X)
4) Uncertainty analysis							
4a) Assessment of uncertainty of input data by:							
Empirical estimates from sample	(X)				(X)	X	X
Non-parametrical tests					(X)	X	X
Data Quality Indicator (DQI)	(X)		X			x	
4b) Error propagation by:							
Monte Carlo simulation	(X)		(X)		(X)	X	
Taylor series expansion	(X)		(X)		(X)	X	
Fuzzy approaches	X		X	X	X	X	
5) Uncertainty importance analysis							
Quantitative uncertainty importance analysis		(X)				X	
Qualitative uncertainty importance analysis	(X)		(X)				

(Own illustration.)

The considered 'uncertainty' always depends on its definition that is used within the applied method. Error propagation with Monte Carlo simulation or Taylor series expansion only treats variability uncertainty in an adequate manner, or even should deal with it. Both methods are based on the concept of probability. Fuzzy approaches allow a consideration of 'uncertainty' in a broader sense basing on possibility and plausibility. Data quality assessment should be considered separate from error propagation. The use of adequate data is the fundamental premise for LCA studies.

Scenario and sensitivity analysis are adequate to analyse specific assumptions. But for a more comprehensive understanding of the LCA model´s behaviour according to uncertainty, uncertainty analysis is convenient. Furthermore uncertainty analysis allows distinguishing between variability and other types of uncertainty.

In LCA literature there is a consensus to distinguish between variability uncertainty and knowledge uncertainty. However, it is not easy achieving it with current methods. Especially the approach within the ecoinvent database is not optimal. When carrying out Monte Carlo simulation the probability distributions should only include variability. Data quality aspects should be treated separately. The manner of Frischknecht et al. (2005) within the ecoinvent database can only be seen as a rough estimation of the probability distributions.

Uncertainty propagation can be assessed by Taylor series expansion, Monte Carlo simulation and fuzzy approaches. Monte Carlo simulation and Taylor series expansion need additional variability information about the input data. Each method has it´s own advantages and disadvantages. Using approximation formulas the total uncertainty can be assessed in an applicable manner. Under unfavourable conditions (non-linearity in the calculation, relatively high random errors), the calculated uncertainty may deviate largely from the true 'uncertainty'.[94] In contrast, Monte Carlo simulation is relatively time-intensive, but is able to treat various types of probability distributions and theoretically can take into account correlations between input parameters. Taylor series expansion is only implemented in LCA software CMLCA[95] of the Institute of Environmental Science of Leiden University. Within this software a potential is seen to deal with various types of uncertainty, in particular to associate knowledge uncertainty and variability uncertainty.

Because of the common use of Monte Carlo simulation in LCA and the potential of uncertainty analysis to deal with important types of variability uncertainty, the further process of this thesis is focussed on these methods. For an adequate assessment of uncertainty propagation within LCA models, it is necessary to obey several requirements. The main requirement is seen in the differentiation between systematic errors (knowledge uncertainty) and random errors (variability uncertainty). Hence, a focus is set to occurring uncertainties within LCI.

To analyse how current LCA studies deal with these requirements and how they counteract the extensive demand on information about data to generate probability distributions, a review of 17 current LCA studies is carried out.

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[94] Cf. CIROTH, A. et al. (2004), p. 217
[95] http://www.cmlca.eu/

3.3 Systematic review of LCA case studies

Last but not least by the requirements of ISO 14044, an increasing awareness of uncertainties within Life Cycle Assessment is visible in the last years.[96]

Parameter uncertainty[97] in LCA studies are analysed extensively. Lloyd and Ries (2007) surveyed 24 studies and all of them considered this type of uncertainty.[98] 13 of these studies used Monte Carlo analysis to investigate uncertainty propagation. In 6 studies the uncertainty is characterised by normal and triangle distributions, in 5 studies by uniform distributions and in 4 studies by lognormal distributions. But in just one case the statistical tests were used to evaluate the goodness of fit of the selected distributions. Further in just 7 of 13 studies parameter correlation is discussed and even in 4 of 13 the correlation is explicit accounted. Data quality indicators are used in 7 studies. 5 of these studies transformed the DQIs into probability distributions. This procedure is criticised by Lloyd and Ries, as a possible source of inaccuracy.[99]

Performing uncertainty analysis when using the ecoinvent database, the problematic procedures of transforming DQIs and neglecting correlation, which may result in unreliable product comparisons[100], may be widely spread.

To analyse if these flaws still exist in uncertainty analysis, especially performing Monte Carlo simulation for uncertainty propagation, a review of 17 LCA studies during the years 2008 till 2011 is carried out. The studies are chosen after the literature research (appendix). Thereby all papers, which include uncertainty analysis for a specific case study carried out with Monte Carlo simulation are analysed. It should be mentioned, that many LCA studies might not be captured, caused by the non-publishing of the studies in the analysed literature databases. Furthermore the published papers may only include summarised information about the procedure of uncertainty treatment.

However, the following questions shall be answered:

- Is it distinguished between variability and other types of uncertainty?
- How do the authors generate probability distributions? Do they use goodness-of-fit tests or do they make assumptions (DQI)?
- Do the authors account for correlations between parameters when performing Monte Carlo simulation?
- Which software is used to carry out uncertainty analysis?

The answers of these questions shall help finding an adequate procedure to deal with uncertainty, which is already applied in LCA studies. The results of the review are discussed for each question.

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[96] Cf. GNAUCK, C. (2009), p. 62
[97] In the study of Lloyd and Ries ‚parameter uncertainty' includes the variability of parameters, according to the definition of Huijbregts.
[98] Cf. LLOYD, S. M.; RIES, R. (2007), pp. 164-178
[99] Cf. LLOYD, S. M.; RIES, R. (2007), p. 174
[100] Cf. LLOYD, S. M.; RIES, R. (2007), p. 175

Table 6: Analysed LCA case studies

2008	2009	2010	2011
Xenakis et al. in Ecological Modelling	Humbert et al. in Internat. Journal of LCA	Röös et al. in Internat. Journal of LCA	Röös et al. in Internat. Journal of LCA
Cordella et al. in Internat. Journal of LCA	De Koning et al. in Internat. Journal of LCA	Langevin et al. in Journal of Cleaner Production	Lucas et al. in Energy Policy
Bojarski et al. in Ind. Eng. Chem. Res.		Renouf et al. in Internat. Journal of LCA	Nemecek et al. in SETAC-Symposium
		Achten et al. in Environmental Science Technology	Stettler et al. in Atmospheric Environment
		Mila I Canals et al. in Internat. Journal of LCA	Venkatesh et al. in Environmental Science and Technology
			Mattila et al. in Journal of Industrial Ecology
			Flysjö et al. in Agr. Systems

(Own illustration.)

3.3.1 Variability uncertainty vs. other types of uncertainty

The first question shall point out how the authors of LCA studies understand uncertainty. It is analysed if the assessed uncertainty is explained in the papers.

During the review of the 17 studies it was conspicuous that the considered 'parameter uncertainty' is not defined in a consistent manner. Each study tends either to the definition of Huijbregts or the definition of Ascough et al. and Björklund, who strictly distinguish parameter uncertainty from variability uncertainty. Especially the studies of the years 2008 and 2009 used the definition of Huijbregts. Four of these studies regarded "parameter/ data uncertainty" (De Koning et al., Bojarski et al., Cordella et al. and Xenakis et al.). On closer examination in all cases the considered type of uncertainty can be described as a type of variability uncertainty. For instance within Cordella et al. (2008) the regarded "data uncertainty"[101], which resulted from different considered processes for beer brewing of the collected data, can as well be described as technological variability uncertainty.

The studies of the years 2010 and 2011 predominantly distinguished between variability and other types of uncertainty. Only in two studies no information can be gathered (Nemecek et al., Achten et al.).

In 4 studies only variability of input data is included when carrying out the study. In 4 studies variability and uncertainty is considered together, and in 2 of the 17 studies (12%) it is distinguished between these types of uncertainty when carrying out uncertainty analysis. Furthermore the analysis shows that in 3 of 17 studies 'uncertainty' is considered, but not explained in a deeper manner (Humbert et al., Nemecek et al., Achten et al.).

[101] CORDELLA, M. et al. (2008), p. 135

Table 7: Differentiation between uncertainties

Differentiation	**"Parameter/ data uncertainty" as a type of variability uncertainty**	**Differentiation between parameter uncertainty and variability uncertainty**			**No statement about the considered uncertainty**
		Only variability considered	*Parameter uncertainty and variability uncertainty considered, but not distinguished*	*Parameter uncertainty and variability uncertainty considered and distinguished*	
Number of studies	4 (23%)	4 (23%)	4 (23%)	2 (12%)	3 (18%)

(Own illustration.)

The review shows that there still exists a lack of a common definition of uncertainty in LCA and further a lack of an obligatory framework dealing with uncertainty. Each study determines the considered uncertainties in a different manner. The explicit attempt to distinguish between variability uncertainty and other types is effected in only 2 of the 17 studies.

Also it seems that an increasing awareness of differentiation between variability and other types of uncertainty has been taken place. The two studies within the differentiation is carried out, are written in the years 2010 and 2011. Otherwise, the same authors (Röös et al.) carried out these studies.

3.3.2 Generation of probability distributions

The generation of probability distributions is the essential requirement for carrying out Monte Carlo simulation. A random variable (input parameter) with an inaccurate mean and hence an inaccurate probability distribution does not lead to correct treatment of variability uncertainty in LCA studies. To analyse how current studies deal with it, the 17 studies are investigated on how the authors determined the distributions and what kind of distributions they used for the simulation.

Table 8: Used types of distribution

Type of distribution	*Lognormal*	*Normal*	*Uniform*	*Triangular*	*Discrete*	*No statement*
Number of studies	11	4	7	3	1	2

(Own illustration.)

The majority of the analysed studies used lognormal distributions to model uncertainty. In eleven studies this type was used. Seven studies used uniform. Normal and triangular were used in 18 % of the studies. In two of the papers no information about the types is given.

The authors of ecoinvent report (2011) argue that the choice of distribution only has a limited influence on overall uncertainty, caused by the central limit theorem whereby the overall uncertainty results in a normal distribution.[102] Furthermore the predominant use of lognormal distribution is reasoned by the frequent observation in real life population and the advanta-

[102] Cf. WEIDEMA, B.P. et al. (2011), p. 76

geous properties of this distribution.[103] The values of lognormal distributed parameters are always positive and the standard deviation is scale independent, which are user-friendly properties.

The manner how the distributions were estimated differs as well. Noticeable is that 53 % of the studies only use assumption based probability distributions. The information about uncertainty is either taken from literature or is based on estimations by experts, e.g. engineers of companies. Four studies used DQIs to generate the distributions. In particular the uncertainty information within the ecoinvent database was taken. In one case a similar approach was used. Within the paper of Mila i Canals et al. (2010) the authors do not go into detail. Also in four studies specific considerations were carried out to determine the distributions more precisely. De Koning et al. (2010) performed a two-step uncertainty analysis. In a first step the authors used the uncertainty distributions of ecoinvent and determined the most important input parameters by sensitivity analysis. In a second step the uncertainty analysis was carried out by updated uncertainty information.[104]

Venkatesh et al. (2011) used goodness-of-fit tests to determine the probability distributions. If it was not possible, because of an insufficient sample, the uniform or triangular distributions were fitted.

Table 9: Generation of probability distributions

Generation of distribution	***With specified consideration (e.g. statistical methods)***	***Data Quality Indicator***	***Only assumptions***	***No statement***
Number of studies	4	4	9	3

(Own illustration.)

The study of Röös et al. (2011) is focused on data variability and other types of uncertainty. Thereby the uncertainty distributions for emission factors contain information about variation and measurement uncertainty and are modelled by lognormal distributions.[105] In some cases the uncertainty distributions are aggregated by the use of DQIs of the ecoinvent database. Within activity data/ primary data they distinguished between variability (e.g. variation between farms and years), expressed by various distributions, and uncertainty (e.g. measurement uncertainty), always expressed by a lognormal distribution.[106] To regard these differences the uncertainty analysis was carried out with scenarios. Thereby the overall uncertainty is calculated either with measurement uncertainty or not.

In a similar manner variability and uncertainty were distinguished in the study of Röös et al. (2010).

No study, in which specified consideration of probability distribution (e.g. statistical methods) was carried out, did regard every single input parameter in a deeper manner. The reasons therefor are additional efforts analysing every single assumption about the type of distribu-

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[103] Cf. WEIDEMA, B.P. et al. (2011), p. 78
[104] Cf. DE KONING, A. et al. (2010), p. 85
[105] Cf. RÖÖS, E. et al. (2011), p. 342
[106] Cf. RÖÖS, E. et al. (2011), p. 343

tion. Also it may be unhelpful to analyse each parameter in most exact manner, if in the end these parameter will not have a significant influence on the result. However, without any analysis the conclusion about the importance of an input parameter is not possible.

3.3.3 Correlations

When performing Monte Carlo simulation, correlations between input parameters should be taken into account. Otherwise the overall uncertainty might be overestimated. The 17 studies are analysed, if this aspect was regarded.

Table 10: Observation of correlations

Taking into account correlations	***No statement***	***Investigated, but not regarded***	***Investigated and regarded***
Number of studies	11 (65 %)	3 (17.5 %)	3 (17.5 %)

(Own illustration.)

Eleven studies do not include information about the consideration of correlations between input parameters. In six cases correlations are investigated and in only 3 of these correlations were taken into account in the simulation. In two studies the aggregation of random numbers resulted by correlation coefficients. In one of these studies no information is given.

3.3.4 Software

There exist several software tools, which support the procedure of Life Cycle Assessment.[107] The advantage of these tools is the possibility to model extensive and complex processes within the life cycle. Also they allow the integration of LCI databases and support the calculation of the potential environmental impact of the analysed products.

The review according to the applied software shall provide information about the potential of LCA software. For example SimaPro, GaBi and openLCA declare the implementation of Monte Carlo simulation. The depth of the implemented MC simulation can only be evaluated by explicit practice. In addition potential approaches of uncertainty analysis shall be provided when using the GaBi software.

In six studies no information about the used software is given. The remaining eleven papers partly used more than one software tool to perform the LCA. The most common software to perform Monte Carlo simulation is SimaPro (47 %). Matlab is used by 18 % of the studies. The rest is distributed to other software tools or no statement is given within the study.

[107] EUROPEAN COMMISSION (Ed.) (2010)

Table 11: Software usage

Software	No statement	SimaPro	GaBi	Matlab	Others
Number of studies	6	8	1	3	3
Correlations regarded in MC simulation	2	-	-	1	1 (SimLab)
Correlations investigated, but not regarded	3	-	-	-	-

(Own illustration.)

Two of the three studies, which declared taking into account correlations within the simulation, give no information about the used software. One study used two different software tools. Thereby, correlation coefficients determined with Matlab and are used within SimLab for MC simulation.

Only in the study of Mila I Canals et al. (2010) the GaBi software was used carrying out the LCA. Within this study a 'variability analysis' is carried out to determine the total variability of the model´s result.[108] Thereby probability distributions are generated to perform Monte Carlo simulation. The variability is assessed for most processing technologies and manufacture at the level of inventory input. Also it was assumed that the variability of all parameters is lognormal distributed. When two or more datasets were available, the distributions were fitted. When only one value was available, a similar way suggested by ecoinvent was used to determine the lognormal distribution with DQIs. This procedure can be evaluated as not optimal, caused by the relating problems (chapter 3.2.4.1). Within GaBi lognormal distribution are not available for Monte Carlo simulation. Thus skewed normal distributions were modelled by adding different values to the lower (-SD) and upper (+SD) bounds of the Monte Carlo assessment of GaBi software.[109]

Within the analysed studies the CMLCA software of Leiden University was not used. This seems to be not comprehensible, because of the high potential of dealing with uncertainties in LCA studies. Reasons therefor might be the absence of a graphical flow interface and the requirement of matrix understanding.

The studies, which used the common LCA software tools SimaPro and GaBi do not give information about potential correlation between input parameters. Carrying out Monte Carlo simulation within these tools, it is not possible to determine correlation coefficients. When using these tools, hence the aim should be to avoid potential correlations between input parameters. Otherwise the determined total uncertainty of the result is overestimated.

3.3.5 Summary

The review of the 17 LCA studies might contain weaknesses during the election of the analysed studies. Only studies are selected, which are published in common literature databases. It is possible that many LCA studies are not published and carried out only for an internal au-

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108 Cf. MILA I CANALS, L. et al. (2010), pp. 53-54
109 Cf. MILA I CANALS, L. et al. (2010), p. 54

dit. Also the published papers usually represent an extract of an extensive LCA study. In contrast to Loyd and Ries (2007), who analysed 24 extensive LCA reports. Thus not the entire necessary information is available and a comparison to the analyses of 2007 is poorly possible.

However, the following statements can be adhered:

When carrying out uncertainty analysis with Monte Carlo simulation, the considered types of uncertainty differ from study to study. Also each paper uses different words to explain these types. Some studies speak about 'uncertainty' without deeper explanation regarding to the occurring types of uncertainty within LCA. Some studies distinguish between variability and parameter/data uncertainty. In several cases it is not possible to comprehend the regarded types in a deeper manner. Hence, there is still a lack of a standardised language, when talking about uncertainties within LCA. In the last two years an increasing awareness of distinguishing between variability uncertainty and other types of uncertainty cannot be evidenced, whether two studies explicitly distinguished between these types.

The determined probability distributions for Monte Carlo simulation are mostly based on fitting to the made assumptions. Only in one case the probability distributions are based on goodness-of-fit tests. The use of DQIs to create the probability distributions is common (4 of 17 studies), but should be critically observed, especially when using other approaches to determine the distributions.

Correlations between input parameters should be considered when carrying out the simulation, either by determining correlation coefficients or by avoiding dependencies between input parameters. It should be mentioned that LCA is a time intensive procedure and in most cases characterised by the use of secondary data. Hence the determination of correlation coefficients is not always applicable.

In addition, the common LCA software tools SimaPro and GaBi do not include the possibility of defining correlation coefficients. The improvident use of Monte Carlo simulation might be result in overestimating the total uncertainty. Nevertheless this seems to be common in current LCA studies, which includes uncertainty analysis by the use of Monte Carlo simulation.

Finally a standardised procedure of dealing with uncertainty, i.e. distinguishing between variability uncertainty and variability uncertainty within LCA could not be detected. Also the procedure within the studies of Röös et al. (2010) and Röös et al. (2011) partly allow the mixture of variability and other types of uncertainty.[110] [111]

Thus, the aim of the following chapter is to develop a methodology, which allows the differentiation between variability uncertainty and knowledge uncertainty. This postulates the observance of these types of uncertainty within the methodology. Furthermore it shall be applicable in the product carbon footprint of the bath powder Blaue Traube.

[110] Cf. RÖÖS, E. (2010), pp. 481-482
[111] Cf. RÖÖS, E. (2011), p. 340

4 Methodology

The resulting problems when mixing knowledge uncertainty, especially information about data quality (systematic error), and variability uncertainty (random error) to one probability distribution are already discussed. Within this chapter a methodology is introduced to deal with uncertainty in a more consistent manner. Thereby the aim is to distinguish between variability uncertainty and knowledge uncertainty. Furthermore the procedure is applied in the product carbon footprint of bath powder Blaue Traube considering the used software tool and LCI databases.

The basics of the introduced methodology are the aggregated unit processes of the ecoinvent-database. Within these processes all emissions, which result in environmental impact, are summarised. The unit processes are connected to model the analysed system. To consider the functional unit the processes have to be connected in certain amounts, e.g. weight of a product or amount of energy. These values can vary in a specific range, e.g. over time. Hence, variability uncertainty exists. The other problem is, that the collected data describing these unit processes of ecoinvent have been carried out for other processes, which do not perfectly represent the analysed system of LCA studies. Hence, knowledge uncertainty arises.

4.1 Variability uncertainty

To consider the variation of amounts, the ranges, within a value is located, have to be detected. Variability uncertainty is expressed by the probability distribution of each amount. To generate the distributions several procedures are available. The most precise option is to test for the distribution. Thereby the condition is to have enough observations. Another way is to determine the minimum and maximum value and fit the distribution. It is obviously that the first option should be preferred, but when carrying LCA studies it may be hopeless to have enough observations and have enough time to analyse. Thus, only the parameters are tested for distribution, which describe the functional unit and besides, which have enough observations.

The probability distributions are then used to carry out a Monte Carlo simulation to determine the total variation of the LCA result.

4.2 Knowledge uncertainty

Knowledge uncertainty is considered by the use of DQIs. Each aggregated unit process is evaluated by the five indicators of the pedigree matrix (table 2, page 13)- reliability, completeness, temporal correlation, geographical correlation and further technology correlation by getting a score for each indicator. Then the total DQI score for each aggregated unit process is calculated. Thereby the subordinated DQI scores are taken and the factors of table 12 are allocated.

Table 12: Concerting-Factors for DQIs

Indicator score	1	2	3	4	5
Reliability	0.000	0.0006	0.002	0.008	0.04
Completeness	0.000	0.0001	0.0006	0.002	0.008
Temporal correlation	0.000	0.0002	0.002	0.008	0.04
Geographical correlation	0.000	0.000025	0.0001	0.0006	0.002
Further technological correlation	0.000	0.0006	0.008	0.04	0.12

(Source: WEIDEMA, B.P. et al. (2011), p. 84)

These factors[112] are usually used in the ecoinvent database to enlarge the percentile-ranges of the probability distributions. Just as well it is possible using them to illustrate the importance of indicator comparing to other indicators. For instance, score 5 of the indicator temporal correlation is more important for the overall data quality than score 5 of geographical correlation.

The following example shall illustrate the procedure:

The aggregated unit process of the surfactant is described by the DQI scores 2,3,5,2,3 for reliability, completeness, temporal, geographical and technological correlation. The total score is now calculated by the equation using the factors of the proceeding table:

Equation 4-1

$$Aggregated\ DQI\ score\ of\ Metaupon = 0.0006 + 0.0006 + 0.04 + 0.000025 + 0.008 = 0.049225$$

Before calculating the aggregated of each process, it is necessary to determine the scores for the five indicators (reliability, completeness, temporal, geographical and technological correlation).

The scores for reliability and completeness are taken from the corresponding unit process (not aggregated) of the ecoinvent database. Within these unit processes the information about the upstream processes is included.

[112] Cf. WEIDEMA, B.P. et al. (2011), p. 84

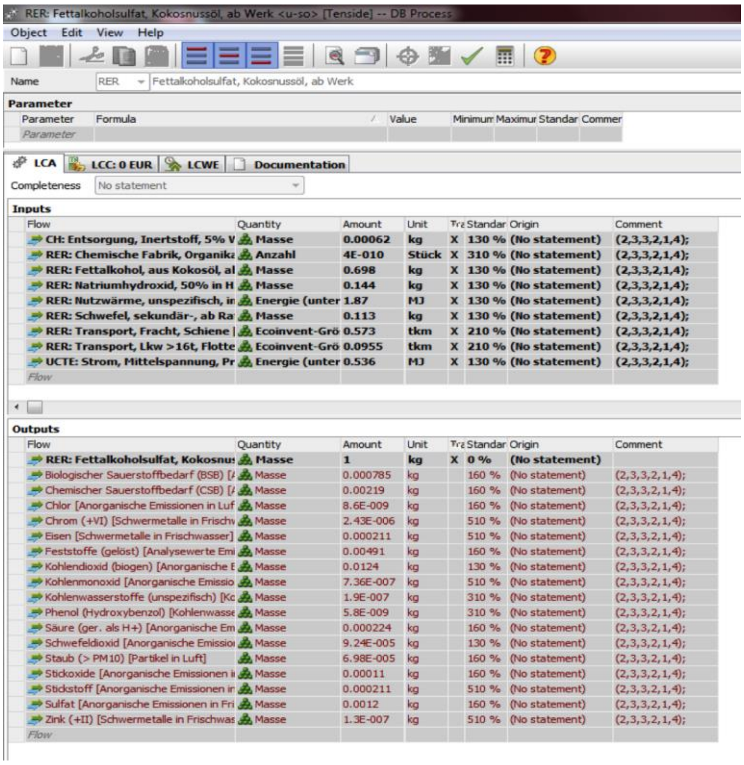

Figure 9: Information about reliability and completeness
(Source: GaBi 5)

Figure 9 illustrates the information of ecoinvent about the unit process "Fettalkoholsulfat, Kokosnussöl, ab Werk", which is used to describe the surfactant of bath powder BT. In the last column ('comment') the indicator scores of inputs and outputs are displayed. The first numbers represent the scores for reliability and completeness of these parameters. According to the introduced example these scores are 2 and 3 in each in and output. Ecoinvent does not always provide adequate information about these values for all processes. In this case the values are estimated, based on the description within the econvent reports[113].

The scores for temporal correlation, geographical correlation and further technological correlation depend on the data quality goals of the specific study. The information about these aspects is included within ecoinvent too. They are taken from the documentation area of the dataset (figure 10).

[113] Cf. ECOINVENT (Ed.) (2003)

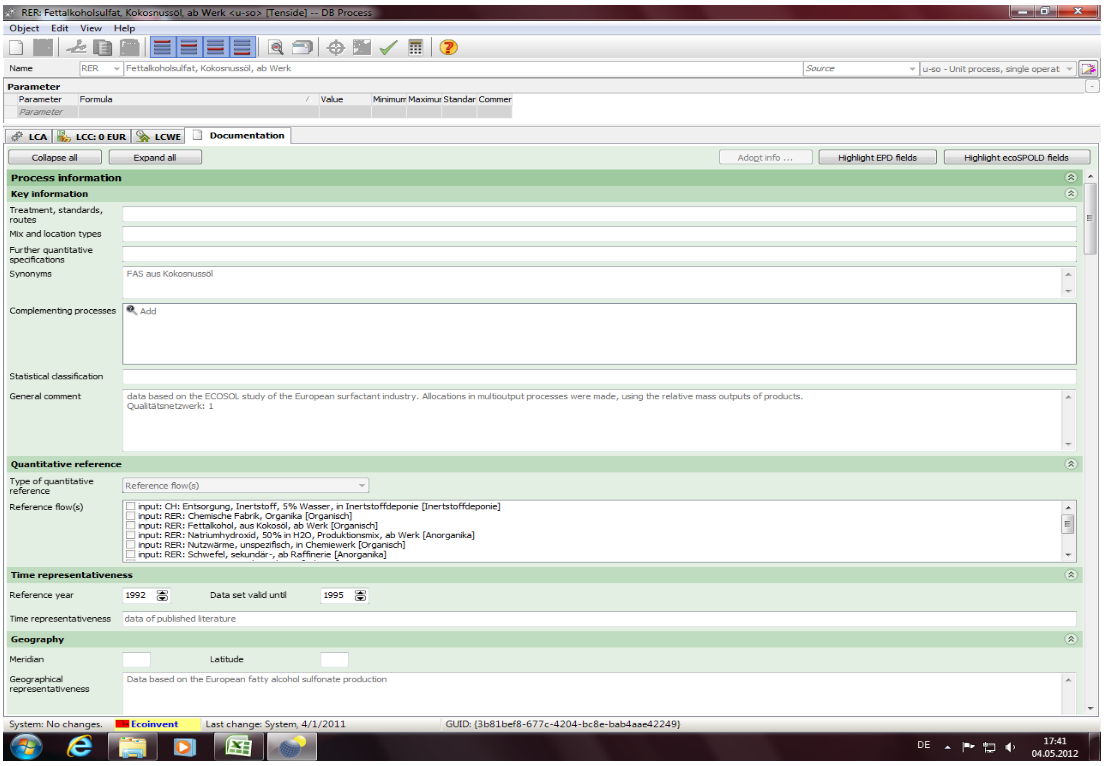

Figure 10: Information about temporal and geographical correlation
(Source: GaBi 5)

The area time representativeness provides the information about temporal correlation. In the example the score 5 is achieved, because the data is described as valid until 1995. The information about the score of geographical correlation is included within the name of the process (RER: Fettalkoholsulfat, Kokosnussöl, ab Werk). "RER" means that the data are representative for European countries. Hence, a score of 2 is achieved, if the data shall be valid for Germany. The most critical indicator is technological correlation. To determine the score for this indicator specific knowledge about the production processes is necessary, which do not exist being not a process engineer of the according industry. Thus, the score of technological correlation is estimated.

4.3 Uncertainty importance analysis

The information about knowledge uncertainty and variability uncertainty are merged within an uncertainty importance analysis. To distinguish between these types the analysis is carried out with the following chart.

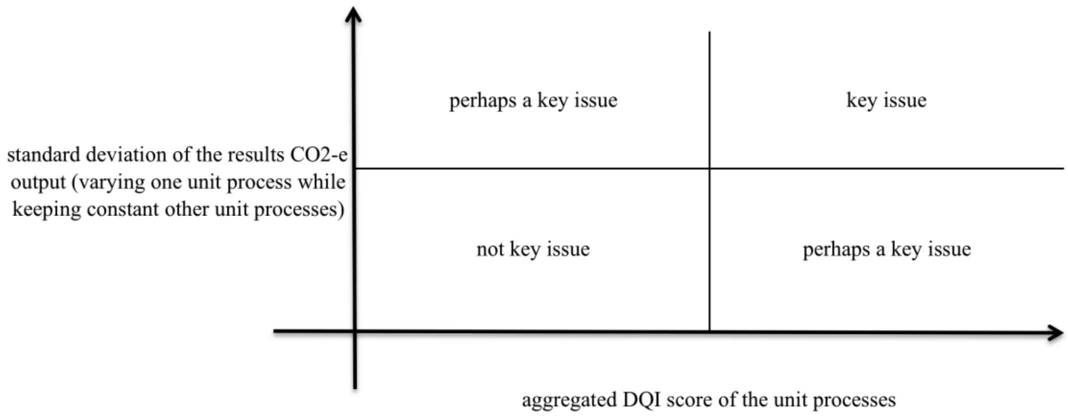

Figure 11: Uncertainty importance analysis
(Own illustration.)

Thereby the x-axis illustrates the total DQI score of each considered aggregated unit process. The y-axis illustrates the contribution to the standard deviation of the total result. That means the results´ standard deviation is calculated by keeping constant all other parameters (similar to equation 3-7, page 23). The analysed process is regarded by performing Monte Carlo simulations 1000 times. Within GaBi software there do not yet exist an integrated approach to identify the most significant parameters according to the overall results´ variation.

The chart is divided into four areas. The dimensions of these areas depend on the highest value, which is achieved by a process. If a process contains both types of uncertainty on a low level, it is called *not key issue*. Containing one type on a low and one type on a high level, it is called *perhaps a key issue*. The problem would arise, if a process contains both types on a high level. That means this process may be based on insufficiently reliable data and contributes to a high variability of the total environmental impact of the analysed product system. The analysis shall identify these *key issues*. For these processes additional data collection is required to enlarge the reliability of the study.

The novelty of the developed concept is the integration of data quality indicators into the key issue analysis[114] of Heijungs and Suh. Considering to the key issue analysis of Heijungs and Suh, where only the quantitative contribution to the variance of the total result is measured, the concept is upgraded by qualitative data aspects of unit processes.

[114] Cf. HEIJUNGS, R.; SUH, S. (2002)

5 Product carbon footprint

The product carbon footprint (PCF) can be interpreted as an impact category of an LCA. When carrying out the study, some principles shall be followed. Thus the PCF study refers to the standards of ISO 14040:2006, ISO 14044:2006 and PAS 2050:2008[115].

According to these guidelines, at the beginning of the PCF study the goals and the scope are identified with the company Li-iL GmbH.

5.1 Goal and scope definition

The main goal is to calculate a PCF of a representative product. This product should play an important role for the company, i.e. it should have a high sales volume and the similarity to the life cycle of other products shall be given. Thus, the product *bath powder Blaue Traube* is chosen for this study. The bath powder BT is used as an additive to the water in bathtubs. It is sold to clients in 60 g packages for single use.

This study should also give a good working example of PCF for possible further LCA-activities of Li-iL GmbH, especially considering further impact categories. The study shall conform to international standards of ISO 14040:2006, ISO14044:2006 and PAS 2050:2008.

In this study, the life cycle steps of bath powder BT, which significantly contribute to the overall PCF, shall be determined. Also this study shall deliver recommendations for producing a more sustainable product.

The results are intended to be used intern. However, the developed procedure for the example product shall provide the basis for publications and shall meet extended requirements for product comparisons.

Furthermore, the methodology dealing with uncertainties, especially variability uncertainty and knowledge uncertainty (chapter 4) shall be implemented.

5.1.1 Data quality requirements

The foundation of LCI data in this study shall be the ecoinvent database 2.2. The database includes over more than 4000 LCI datasets in the areas of agriculture, energy supply, transport, biofuels, bulk and speciality chemicals, construction materials, packaging materials, metals, electronics and waste treatment.[116] Furthermore the database offers high consistency and transparency by the extensive documentation of datasets.

Dealing with knowledge uncertainty and variability uncertainty in accordance to have valid results and to give right recommendations the developed methodology from chapter 4 is used.

To meet the requirements of ISO 14044 each used unit process, either taken from ecoinvent or from other literature, is analysed according to data quality goals (DQG). These goals are the foundation of the indicator scores of each unit process. These DQIs represent the knowledge uncertainty.

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115 Cf. CARBON TRUST et al. (Eds.) (2008)
116 Cf. http://www.ecoinvent.org/database/

The following goals should be achieved:

- Reliability: The collected data should be verified and based and measurements.
- Completeness: The collected data should represent all representative processes of Li-iL GmbH within Germany and Europe. Data gaps have to be avoided. The discussed Cut-off is allowed.
- Temporal goal: The collected data should regard the year 2011.
- Geographical goal: The collected data should represent the real case of Li-iL GmbH in Dresden (Germany) as well as its real deliverers and clients.
- Technology coverage goal: The collected data should consider the technological processes, which are used to produce the product with its pre-products and its transport.

The information about variability uncertainty is collected directly in accordance to the specific situation of the life cycle of bath powder BT. Thereby the demand of unit processes can vary in a certain range. To detect this range the minimum and maximum values have to be determined. If enough data observations are available, the probability distribution of the sample is tested. Otherwise the observed minimum and maximum values are applied by the following standard procedure.

To consider the variability in the amounts of unit processes it is assumed that each value is normally distributed. The approximate standard deviation is calculated by dividing the range (max value – min value) by 3.[117] In other words it is assumed that the observed min-and max-values represent the 0.0668-and 0.9332-quantile of the normal distribution (86.64% of all possible values are in this range). The distributions either are cut or not. Cutting distributions is done at the observed minimum and maximum value, whether it is not realistic being lower or upper these values. The procedure also avoids negative values.

The information about the considered variability uncertainty and knowledge uncertainty is given in the LCI phase (chapter 5.2).

5.1.2 Functional Unit

To achieve the goals, especially delivering recommendations to the company, the functional unit is set to *one bath in a bathtub*. The functional unit includes the following three parts:

- Bath powder
- Packaging materials
- Rationing of tap water

The amounts of these parts can vary in a specific range depending on technological and human circumstances.

To determine the range of the packaged powder a sample of 100 fill quantities is analysed by a Chi-square goodness-of-fit test. This test provides a mean of 60.67 g filled powder. In addition, the test allows the verified assumption of a normal distributed population with a standard deviation of 0.471 g (0.78%).

[117] Cf. WEIDEMA, B.P. et al. (2011), p. 80

The packaging materials of BT contain the multilayer film, the corrugated cardboard box and the display. The amounts of these materials can also vary slightly. For better overview the regarded amounts are illustrated in the inventory analysis (chapter 5.2).

The content of bathtubs differ between households. It is assumed that the majority have bathtubs with a capacity of 160 litres. The considered bathtubs shall vary in a range between 120 and 200 litres.

5.1.3 Cut-off criteria

Life cycle assessment in general, and product carbon footprints in particular are data and time intensive procedures. To handle with these characteristics it is possible to define cut-off criteria.[118]

The part of the functional unit, which is responded by Li-iL GmbH, consists of two parts: bath powder BT and packaging materials. The ingredients of the powder are 13 pre-products, which are weighted and mixed in the production site of Li-iL GmbH. Making the considered model more simple but still valid only the ingredients are included, which have a rate of at least 1 % to the overall mass of the powder (cut-off of < 1 % mass). This leads to a total cut-off of 1.76 % mass. It is assumed by the research-and-development-manager of Li-iL GmbH and the author of the study that the excluded ingredients will not have a significant effect to the overall environmental impact. The included and excluded ingredients of the powder are marked in table 13.

Table 13: Cut-off ingredients

Part of functional unit	***Ingredient***	***Mass ratio***
Bath powder BT	Surfactant	1-5 %
	Defatting agent A	1-5 %
	Defatting agent B	0.1-1 %
	Active agent A	0.1-1 %
	Colour magenta	< 0.1 %
	PH-adjustment	< 0.1 %
	Defatting agent C	1-5 %
	Fragrance	1-5 %
	Active agent B	0.1-1 %
	Colour blue	< 0.1 %
	Base A	> 75 %
	Base B	1-5 %
	Fragrance	0.1-1 %
	Total considered	98.24 %

(Own illustration.)

There also exist cut-offs of packaging materials. Not considered are stickers, which are glued on the cardboard box, as well as other negligible materials.

[118] Cf NAGUS (Ed.) (2006b), pp. 18-19

5.1.4 Product System and System Boundary

The global warming potential shall be determined over the whole life cycle of the bath powder BT (cradle-to-grave). Hence the system boundary includes the steps appropriation of pre-products, manufacturing and distribution of bath powder BT 60g, utilisation (including tap water) and end-of-life treatment. The appropriation includes all transport processes, which are necessary to deliver the goods from their plants to Li-iL GmbH. The manufacturing phase does not include the building hall and associated land use and delivering of building materials. The distribution to clients considers the transport of the product. Potential storage processes, e.g. in distribution centres are not included. Within the utilisation tap water is regarded to evaluate the total impact of the use of the analysed bath powder and to calculate a ratio of the environmental impacts of processes, which are in the responsibility of the company and which are not. The end-of-life phase regards the disposal of the tap water, including the bath powder, and the disposal of the packaging materials.

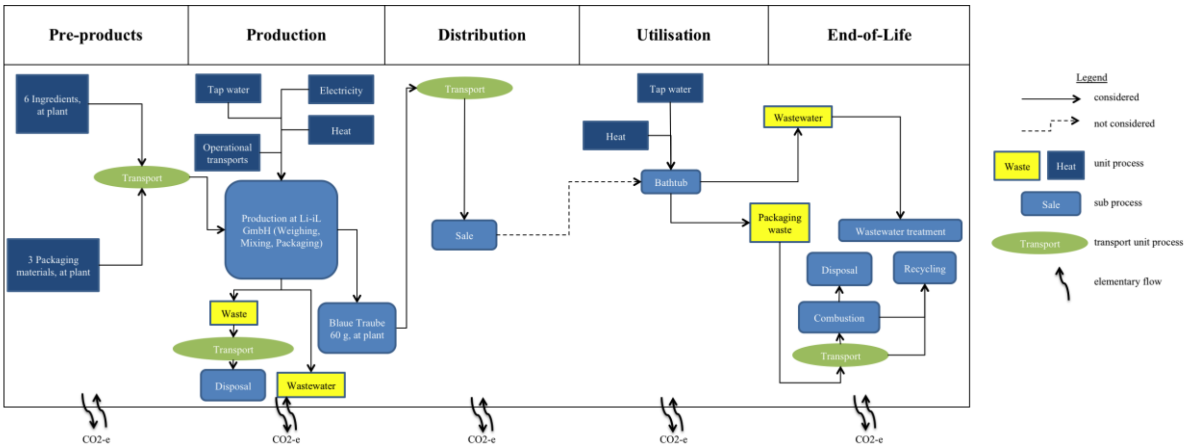

Figure 12: Product system and system boundary of bath powder BT (Own illustration.)

Because of reasons of clearness the simplified figure only reflects the most important unit processes of the product system. The light blue sub processes within the flow chart are just illustrated to visualize the life cycle. These sub processes are indirectly considered during modelling. All unit processes and its data are discussed in the further chapters.

5.2 Life cycle inventory (LCI)

The life cycle inventory analysis includes the collection of data, the calculation of data and allocation rules, which are used to create the unit processes. To make it more clearly arranged the unit processes are shown and discussed separate for every step of the life cycle (appropriation of pre-products, manufacturing, distribution, utilisation and end-of-life). Generally all aggregated unit processes of the ecoinvent 2.2-database are illustrated. If adequate processes or substances are not yet included in the database, it is tried either finding similar processes within the database and connecting ecoinvent processes or carrying out literature research. The resulting greenhouse gas emissions are not displayed in this section. They are calculated as CO2-e in chapter 5.3 by using the GaBi 5-Software.

To increase the understanding of the German target group, it is decided to illustrate the used ecoinvent processes by their German denomination.

5.2.1 LCI of pre-products

The first step of the analysed life cycle of Blaue Traube consists of the production of the pre-products (ingredients and packaging materials) and its transportation from the production site to the factory of Li-iL GmbH. Considering the cut-off criteria in chapter 5.1.3, six ingredients remain for the analysis. The packaging materials are the multilayer film for the 60 g package of the bath powder, the display for decoration in stores (a display contains ten 60 g packages) and the corrugated cardboard box for the transportation of ten filled displays.

The ingredients can vary too, caused by a weighing process before mixing the several ingredients. The range is specified in a working instruction of the company by a target value, a minimum and a maximum. The target value represents the mean of the assumed normal distribution. The distribution is cut at the min and max values.

Table 14: Variability uncertainty of ingredients

Unit process (ingredient)	***Mean in g***	***Standard deviation in %***	***Distribution***	***Min-Max in g***
Surfactant		1.26%	Normal	
Defatting agent A		0.94%	Normal	
Defatting agent B		0.76%	Normal	
Fragrance		0.77%	Normal	
Base A		0.05%	Normal	
Base B		0%)	-	-

(Own illustration.)

In the same manner the three packaging materials are treaded (table 15). The mass of the multilayer film can vary slightly (estimated by a sample of 10 packages). According to the included 10 multilayer films in one display and 10 filled displays in one corrugated cardboard the variations of the displays/ cardboards masses are negligible.

Table 15: Variability uncertainty of packaging materials

Unit process (packaging material)	***Mean in g***	***Standard deviation in %***	***Distribution***	***Min-Max in g***
Multilayer film	3.75	0.89%	Normal	3.70-3.80
Display	3.73	0%	-	-
Corrugated cardboard	2.445	0%	-	-

(Own illustration.)

The transport distances (production site to the factory of Li-iL) of each pre-product are summarised in table 16. The distances are identified with Google-maps[119] and represent the optimal way between the production sites and Li-iL GmbH. They do not include distances to distribution centres etc. Hence these values are quite optimistic and may need further observa-

[119] www.maps.google.com

tions. The ton kilometres (tkm) represent the transported product (in t) over a certain distance (in km). The road transports are summarised to one process (0.01696 tkm). This value can be interpreted as a minimum value. The maximum value of transport capacity is determined by multiplying with a factor of 1.3 (max=0.02205 tkm). It is assumed that the pre-products are transported on road by lorry with the Euro efficiency class 4.

Table 16: Transport distances of pre-products

Pre-Product	***Surfactant***	***Defatting agent A***	***Defatting agent B***	***Fragrance***	***Base A***	***Base B***	***Multilayer film***	***Display***	***Corrugated cardboard***
Km	149	498	464	495	238	98.4	408	82.3	63.8
tkm							0.00153	0.00031	0.00016

(Own illustration.)

The considered variability of cumulated transports is illustrated in the following table. To avoid negative and unrealistic values the normal distribution is cut at the minimum and maximum.

Table 17: Variability uncertainty of cumulated transports

Unit process	***Mean in tkm***	***Standard deviation (%)***	***Distribution***	***Min-Max***
Cumulated transports	0.01951	0.0017 (8.7 %)	Normal	0.01696-0.02205

(Own illustration.)

There are several substances for which no adequate unit process of the ecoinvent database already exists. This could be seen as a data gap. Dealing with this problem either equal processes were used or new unit processes were modelled by using other unit processes of the ecoinvent database. Both cases will induce a higher uncertainty, more than may already exist before. Taking this into account the data quality indicators are determined for each data set, which represents the analysed ingredients, packaging material and its transport. All examined substances and its ecoinvent equivalents are visible in in the following table.

Considering the data quality requirements each modelled process/ substance has been evaluated by the scores of the five indicators of the pedigree matrix (page 13). This procedure shall ensure the reliability of the results by taking into account additional sources of uncertainty. The scores are determined to the explicit requirements of chapter 5.1.1.

Table 18: Knowledge uncertainty of pre-products

	Unit process	***Amount***	***Ecoinvent process***	***DQI scores***	***Aggr. DQI score***
Ingredients	Surfactant			2,3,5,2,3	0.04925
	Defatting agent A			1,4,2,5,4	0.0442
	Defatting agent B			2,2,3,1,1	0.0027
	Fragrance			5,5,3,3,3	0.0581
	Base A			4,5,4,5,3	0.034
	Base B			5,5,3,1,1	0.05
Packaging materials	Multilayer film	3.70-3.80 g	RER: Verpackungsfolie LDPE, RER; Aluminium Produktionsmix, DE: Metallkleber, RER: Transport Lkw 7.5-16t Euro4	3,5,5,1,3	0.058
	Display	3.73 g	RER: Chromokarton FBB	2,4,4,3,1	0.0107
	Corrugated card-board	2.445 g	RER: Wellkarton gemischte Fasern, einwellig	1,2,3,1,3	0.0101
Transport	Cumulated trans-ports	0.01696 - 0.02205tkm	RER: Transport Lkw 7.5-16t Euro4	3,1,3,2,2	0.00465

(Own illustration.)

Four substances could not be modelled with the ecoinvent database: defatting agent A, fragrance, base B and multilayer film.

Modelling fragrance may be the most difficult challenge.

Multilayer film for the 60g package of Blaue Traube consists of a total glue of 4.5 µm and the three layers PETP (12 µm), Aluminium (12 µm) and PE-LD (75 µm). Also for this type of multilayer film no data set does yet exist in ecoinvent. The two plastic layers are modelled with the aggregated data set *"RER: Verpackungsfolie-LDPE, ab Werk"*. Aluminium layer is modelled with *"RER: Aluminium, Produktionsmix, ab Werk"*. The glue between the three layers is considered by *"DE: Metallkleber, ab Werk"*. The production site, which converts the raw materials, is not included. Only delivery transports of the four raw materials are collected. Per 1 kg multilayer film the total amounts are 0.849 kg *"Verpackungsfolie-LDPE"*, 0.117 kg *"Aluminium"*, 0.034 kg *"Metallkleber"* and 0.2 tkm *"Transport, Lkw"*.

Defatting agent A could not be modelled with the ecoinvent database. Also no similar processes within the database are included. Thus a literature search was carried out to find a LCA study about defatting agent A. This search did not succeed for the agent. Hence it was decided to use data of a LCI study

5.2.2 LCI of manufacturing

The delivered ingredients of Blaue Traube are mixed at the factory of Li-iL GmbH. After this process step the 60 g of this granulate is filled into the package film, then packed into the display and finally into the corrugated cardboard. For modelling these steps primary data is collected from company data of Li-iL GmbH. This includes the amounts of electricity, water and heat usage, waste and wastewater generation, as well as inner operational transport distances. The construction of the building and the appropriation of the machines are not regarded.

Regarding the functional unit, data for these amounts are not explicit available at the company. To allocate the amounts to one 60g package a mass allocation approach is used. For electricity monthly data of the total electricity consumption in September to November 2011 is used. Further it is assumed that all produced products of Li-iL GmbH require the same amounts of electricity, heat and waste. Hence the following equation is used to allocate the electricity to one package of Blaue Traube.

Equation 5-1

$$\boldsymbol{Electricity_{BT,i}}\ [kWh/piece] = \frac{Electricity_{total,i}[kWh]}{Total\ amount\ _i[pieces]}$$

The total amount of produced products from September to December 2011 is 4477260 pieces. Thus the average per month is 1119315 pieces.

In November 2011 the electricity consumption for one package is:

Equation 5-2

$$Electricity_{BT,Nov.} = 20431\ kWh\ /\ 1119315\ pieces = 0.01825 \frac{kWh}{piece}$$

The electricity consumption in October 2011:

Equation 5-3

$$Electricity_{BT,Oct.} = 20427\ kWh\ /\ 1119315\ pieces\ = 0.01825 \frac{kWh}{piece}$$

The electricity consumption in September 2011:

Equation 5-4

$$Electricity_{BT,Sept.} = 18.236\ kWh\ /\ 1119315\ pieces = 0.01629 \frac{kWh}{piece}$$

Also the amounts of heat, waste, operational and waste transports are allocated. Data for these values are only available per annum. The total consumption of heat in 2011 was 317000 kWh.

Equation 5-5

$$\boldsymbol{Heat_{BT,i}}\ [kWh/piece] = \frac{Heat_{total,2011}[kWh]}{12}\ /\ Total\ amount\ _i[pieces]$$

Heat consumption per month:

Equation 5-6

$$Heat_{BT,monthly} = \frac{317000\ kWh}{12} / 1119315\ pieces = 0.0236 \frac{kWh}{piece}$$

Waste generation of the company is divided into the four categories residual waste, paper and board, fluorescent lamps and hazardous waste.

Equation 5-7

$$\boldsymbol{Waste_{BT,i}}\ [g/piece] = \frac{Waste\ _{category,2011}[g]}{12} /\ Total\ amount\ _i[pieces]$$

Waste per month:

Equation 5-8

$$Residual\ waste_{BT,monthly} \coloneqq \frac{15810000g}{12} / 1119315\ pieces = 1.17706 \frac{g}{piece}$$

Equation 5-9

$$Paper\ and\ board_{BT,monthly} \coloneqq \frac{20000000g}{12} / 1119315\ pieces = 1.48901 \frac{g}{piece}$$

Equation 5-10

$$Fluorescent\ lamps_{BT,monthly} \coloneqq \frac{65000g}{12} / 1119315\ pieces = 0.00484 \frac{g}{piece}$$

Equation 5-11

$$Hazardous\ waste_{BT,monthly} \coloneqq \frac{16750000g}{12} / 1119315\ pieces = 1.24704 \frac{g}{piece}$$

Within the year 2011 fifty fluorescent lamps were disposed. It is assumed that one lamp have a weight of 1.3 kg.

Determining the exact transport distance of the several waste types would be quite time-consuming proportional to its environmental effect. Thus the average distance of waste transport is assumed to be 200 km. The total transport capacity of waste is 0.00078 tkm.

Equation 5-12

$$\begin{aligned}\boldsymbol{Waste\ transports}\ [tkm/piece] \\ &= 200km * (1.177g/piece + 1.489g/piece + 0.005g/piece + 1.247g/piece) \\ &= 0.00078\ tkm\end{aligned}$$

In 2011 the operational transports were 173000 km. This distance includes all passenger cars of the company.

Equation 5-13

$$\begin{aligned}\boldsymbol{Operational\ Transports}\ [pkm/piece] &= \frac{Transports_{total,2011}[pkm]}{12} / Total\ amount_i\ [pieces] \\ &= 0.01288\ pkm/piece\end{aligned}$$

The regarded amounts of water and wastewater can be calculated directly. Within the production of Blaue Traube powder only water is used to clean the boxes, in which the powder is mixed. Thereby 40 to 50 litres water is necessary to clean one box. In one box two charges of 350 kg powder are produced. Thus the regarded amount of water to produce 60.67 g powder is 0.0039 litres ±10 %. The total range is located between 0.00351 and 0.00429 litres per unit.

All unit processes of the production within the life cycle are summarised in table 19. Furthermore the information about knowledge uncertainty (expressed by the aggregated DQI score of each process) is illustrated.

Table 19: Knowledge uncertainty of production

Unit process	***Amount***	***Ecoinvent process***	***DQI score***	***Aggr. DQI score***
Electricity	0.01629-0.01825 kWh	DE: Strom, Niederspannung (Versorgungsmix)	3,1,3,2,3	0.01205
Heat	0.0236kWh	RER: Nutzwärme, ab Heiz-kessel kond. mod. >100kW	4,1,4,2,2	0.01665
Water	0.00351-0.00429 kg	RER: Trinkwasser, ab Hau-sanschluss	2,3,4,2,2	0.00985
Wastewater	0.00351-0.00429 kg	CH: Behandlung, Abwasser Gr. Kl. 1	2,2,4,3,2	0.0094
Residual waste	1.17706 g	CH: Entsorgung Siedlungs-abfall, in Kehrrichtverbren-nung	2,2,4,3,3	0.018
Paper and board	1.48901 g	RER: Altpapiersortierung für Verarbietung	4,3,2,3,2	0.0095
Fluorescent lamps	0.00484 g	GLO: Entsorgung Leuchtstoffröhren (Recy-cling)	4,4,3,3,3	0.0201
Hazardous waste	1.24704 g	CH: Entsorgung Sonderab-fall 25% Wasser in Sonder-abfallverbrennung	1,1,4,3,3	0.0161
Operational transports	0.01288 pkm	RER: Transpor Pkw, Ben-zin, Flottendurchschnitt 2010	3,1,1,2,2	0.00265
Waste transports	0.00078 tkm	RER: Transport, Lkw >16t Flottendurchschnitt	3,1,3,2,2	0.00465

(Own illustration.)

The information about variability uncertainty are summarised in the following table. The probability distributions are not cut.

Table 20: Variability uncertainty of production

Unit process	***Mean***	***Standard deviation (%)***	***Distribution***	***Min-Max***
Electricity	0.01727 kWh	0.00065 (3.76 %)	Normal	0.01629-0.01825 kWh
Water	0.0039 kg	0.00026 kg (6.67%)	Normal	0.00351-0.00429 kg
Wastewater	0.0039 kg	0.00026 kg (6.67%)	Normal	0.00351-0.00429 kg

(Own illustration.)

5.2.3 LCI of distribution

Within the distribution phase, the transport from the factory of Li-iL GmbH in Dresden to the shops is considered. The storage in distribution centres and the shops is not included.

The distance between the factory of Li-iL GmbH and the shop is assumed to be 170 km.

Table 21: Knowledge uncertainty of distribution

Unit process	***Distance***	***Ecoinvent process***	***DQI score***	***Aggr. DQI score***
Transport (distribution)	170 km	RER: Transport, Lkw 7.5-16t, EURO4	3,1,3,2,2	0.00465

(Own illustration.)

The assumed transport distance is quite subjective. To determine the influence of other assumptions a scenario analysis is carried out in further proceeding. In that an enlarged transport distance to Japan is analysed.

5.2.4 LCI of utilisation

After the distribution of the product to a shop, clients buy the 60 g package of Blaue Traube. The manner how people buy products can vary. It is possible going by car or by bike or by other means. The purchase might be attended by many other benefits, e.g. buying other products or getting to work. Distinguishing these benefits and allocating the environmental effects to one package of Blaue Traube is considered as not feasible and redundant. Hence the shopping tour is not included within the study.

The production and the delivery of tap water to households are considered in the analysis. The content of bathtubs can vary between 120 and 200 litres. It is assumed that a content of 160 litres is most probable for all scenarios. A normal distribution is created with the following properties. The distribution of heat is cut.

Table 22: Variability uncertainty of utilisation

Unit process	***Mean***	***Standard deviation (%)***	***Distribution***	***Min-Max***
Tap water	160 litres	26.67 (16.67 %)	Normal	120-200 litres
Heat	8.2 kWh / 160 l	2 (24.39 %)	Normal	5.2-11.2 kWh / 160 l

(Own illustration.)

The tap water is modelled with the ecoinvent process "RER: Trinkwasser, ab Hausanschluss".

The required energy heating the tap water is determined by the following formula:

Equation 5-14

$$W = m * c * \Delta\theta = 159.952\ kg * 4.1826 \frac{J}{K*g} * 28\ K = 18732.43\ kJ$$

with:

- m is the mass of the tap water with 10°C:

Equation 5-15

$$m = p * V := 999{,}7 \frac{kg}{m^3} * 0.16 m^3 = 159.952\ kg$$

- c is the specific heat capacity for water:

Equation 5-16

$$c = 4.1826 \frac{J}{K*g}$$

- Δθ is the difference of temperature between 10°C and 38°C:

Equation 5-17

$$\Delta\theta = 28\ K$$

- 1kWh=3600kJ

The required energy is hence 5.203 kWh per 160 litres.

Calculated with the formula §9 (2) Heizkostenverordnung 2009[120]:

[120] Cf. BFW (Ed.) (2009)

Equation 5-18

$$E = 2.5\frac{kWh}{m^3*K} * V * (t_w - 10\ °C) = 2.5\frac{kWh}{m^3*K} * 0.16m^3 * 28K = 11.2\ kWh$$

- t_w is the temperature of tap water (38°C)

The information about knowledge uncertainty is summarised in the following table.

Table 23: Knowledge uncertainty of utilisation

Unit process	***Amount***	***Ecoinvent process***	***DQI score***	***Aggr. DQI score***
Tap water	120-200 litres	RER: Trinkwasser, ab Hausanschluss	2,3,4,2,2	(0.00983)
Heat	5.2-11.2 kWh / 160	RER: Nutzwärme, Erdgas, ab Heiz-kessel mod. <100kW	2,1,4,2,2	(0.00923)

(Own illustration.)

It shall be used a common energy sources to warm the water. In Austria during the years 2009 and 2010 electricity (26.8 %) and natural gas (22.7 %) were the most common energy sources for this process.[121] Hence, the energy source natural gas is assumed.

5.2.5 LCI of end-of-life

Within the end-of-life phase the disposal of tap water and packaging material is included. The average amount of wastewater is 160 litres and includes the Blaue Traube powder. Packaging materials are the corrugated cardboard box, the display and the multilayer film. It is assumed that the display and the cardboard are disposed in containers for recovered paper and board, which then can lead to the production cycle. Wastewater is treaded in a wastewater treatment plant with a capacity class 1 (highest class).

The variability of each unit process is determined by a normal distribution. The information about variability uncertainty is taken from the proceeding chapters 5.2.1 and 5.2.4. Because no variations in the amounts of the display and the cardboard box could be detected, the two processes can be combined. Furthermore it is assumed, that both products are delivered to the collection of wastepaper.

Table 24: Variability uncertainty of end-of-life

Unit process	***Mean***	***Standard deviation (%)***	***Distribution***	***Min-Max***
Wastewater treatment	160 litres	26.67 (16.67 %)	Normal	120-200 litres
Disposal of multilayer film	3.75 g	0.033 (0.89%)	Normal	3.70-3.80
Disposal of cardboard and display	6.175 g	-	-	-

(Own illustration.)

All unit processes and the information about knowledge uncertainty are illustrated in the following table.

[121] Cf. STATISTIK AUSTRIA (Ed.) (2011)

Table 25: Knowledge uncertainty of end-of-life

Unit process	*Amount*	*Ecoinvent process*	*DQI score*	*Aggr. DQI score*
Wastewater treatment	120-200 litres	CH: Behandlung, Abwasser, in Abwasserreinigung, Gr.Kl. 1	2,2,4,3,2	0.00188 (0.0094)
Disposal of multilayer film	3.70-3.80 g	CH: Entsorgung, Siedlungsabfall, 22.9% Wasser, in Kehrichtverbrennung	2,2,4,3,3	0.00336 (0.0168)
Disposal of cardboard and display	6.175 g	RER: Altpapier, gemischt, aus Sammlung, für Verarbeitung	5,4,4,2,4	0.01805 (0.09025)

(Own illustration.)

5.3 Impact assessment and interpretation

The analysis of life cycle impact results is carried out at two system boundaries. First the whole life cycle of Blaue Traube is investigated to determine the overall impact of one bath in a bathtub (cradle to grave). In a second step only the production of Blaue Traube is considered (cradle to gate). The aim of the analysis is to point out the room of improvement, which is in the direct responsibility of Li-iL GmbH.

To improve the reliability of the carbon footprints (cradle-to-grave and cradle-to-gate) several scenarios are analysed next to the basic assumptions, which are already explained in the preceding chapters. In addition, for each scenario uncertainty analysis are carried out to determine the total variation of the carbon footprint. Also uncertainty importance analysis is performed to distinguish the processes, which are most relevant for the variation of the footprint (variability uncertainty) and which may affect the reliability, according to the quality of data (knowledge uncertainty).

The carbon footprint is calculated with the Global Warming Potential (100 years) of CML 2001- Nov. 2010 in the GaBi 5 software.

5.3.1 Cradle to grave

The aim of the study is to determine the carbon footprint of one bath in a bathtub. This includes the consideration of the whole life cycle including pre-products, production, distribution, utilisation and end-of-life of Blaue Traube.

Regarding the described assumptions (basic case) within the model, the total carbon footprint of one bath in a bathtub with Blaue Traube powder is 2.466 kg CO2-e.

Thereby the utilization is the most important phase of the life cycle. This life cycle step contributes to 93.2 % (2.298 kg CO2-e) of the total carbon footprint. Within the utilisation the dominant process is the heating of tap water. The assumed heating of tap water from 10°C to 38°C (8.2 kWh per 160 litres) with natural gas in a boiler contributes with 2.249 kg CO2-e to 91.2% of the overall footprint.

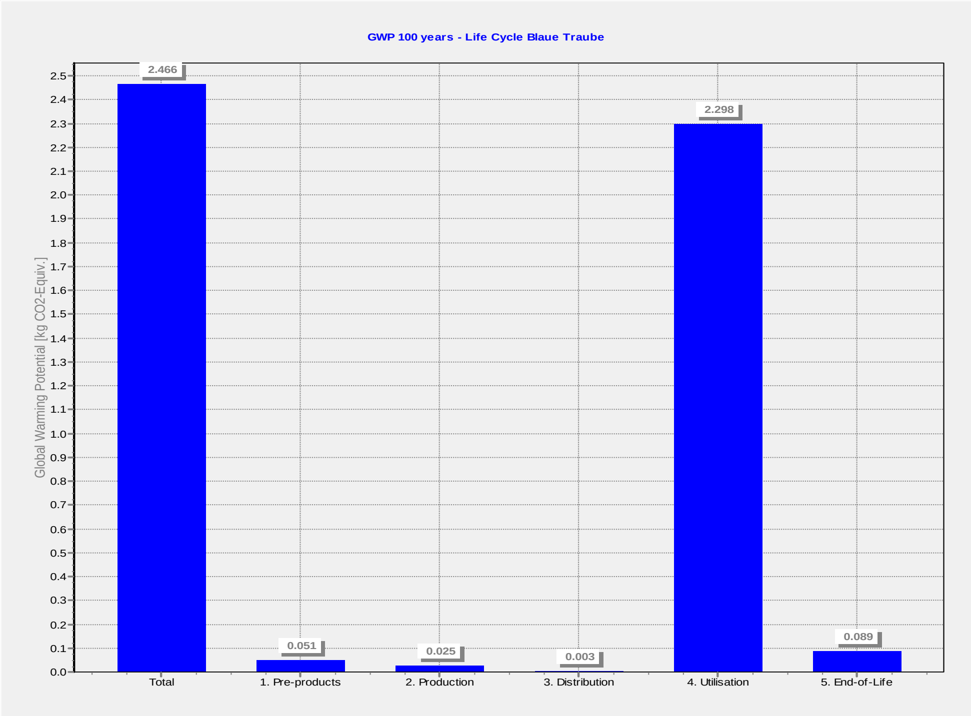

Figure 13: GWP of basic case, cradle-to-grave
(Source: GaBi 5)

The end-of-life phase has a ratio of 3.6 % (0.089 kg CO2-e) on the overall footprint.

The appropriation of pre-products and the further processing of these products to one package of Blaue Traube with its packaging materials together contribute to 3.1 % (0.076 kg CO2-e) of the footprint.

5.3.1.1 Scenario analysis

To analyse how different assumptions and future situations affect the carbon footprint, scenarios are developed. These scenarios can be arranged into the three groups transport, pre-product and heating scenarios.

Within the distribution of the 60g packages of Blaue Traube a transport distance to shops of 170 km was assumed. It is also possible to deliver one package over longer distance. And in future it may be possible to deliver Blaue Traube to other continents. Thus, the following transport scenario is analysed. The transport scenario considers a road transport of 500 km and a ship transport of 21167 km[122] from Hamburg (Germany) to Tokyo (Japan).

When producing Blaue Traube powder it is possible to substitute the ingredient base A by the alternative base A

A transport distance of 1425 km[123] between Salin-de-Giraud (France) and Dresden is assumed. The total transport of pre-products is summarised to one process, according to the procedure in chapter 5.2.1. Also this distance is assumed to be an optimal case. Thus the total

[122] www.searates.com
[123] www.maps.google.com

transport capacity of 0.07195 tkm is multiplied by the factor 1.3 to estimate the maximum of 0.09354 tkm. The mean determines 0.08275 tkm with a standard deviation of 8.7 %.

Heating the tap water is analysed as the most important process within the cradle-to-grave consideration. To analyse how other heating procedures besides natural gas influence the footprint, two heating scenarios are introduced. The first heating scenario is characterised by a pellet heating system to warm the water. The second heating scenario considers the case of combined usage of solar thermal collectors and gas heating.

All scenarios and the information about knowledge uncertainty are summarised in the following table.

Table 26: Analysed scenarios

Scenario category	***Scenario***	***Amount***	***Ecoinvent process***	***DQI score***	***Aggr. DQI score***
1) Transport	1) Ship and road transport	0.0353 tkm (road)	RER: Transport, Lkw 7.5-16t, EURO4	3,1,3,2,2	0.00465
		1.4923 tkm (ship)	OCE: Transport, Frachter Übersee	2,2,4,1,2	0.0093
2) Pre-product	2) Alternative base A			2,4,1,3,2	0.0033
		0.07195 tkm (total)	RER: Transport, Lkw 7.5-16t, EURO4	3,1,3,2,2	0.00465
3) Heating	3a) Pellet heating	5.2-11.2 kWh / 160 litres	CH: Nutzwärme, ab Pelletsheizung 15kW	1,2,4,3,2	0.0088
	3b) Solar thermal heating and Gas	5.2-11.2 kWh / 160 litres	CH: Nutzwärme, ab Warmwasserspeicher, Flachkollektor, Mehrfamilienhaus, Gasheizung	2,4,3,3,2	0.0053

(Own illustration.)

5.3.1.1.1 Results of scenario 1

The extension of the transport distance does not contribute to a significant change of the carbon footprint. An additional amount of 0.021 kg CO2-e (+0.9 %) arises, if the 60g package would be delivered to Japan.

The total carbon footprint of one bath in a bathtub with bath powder BT is 2.487 kg CO2-e (figure 14).

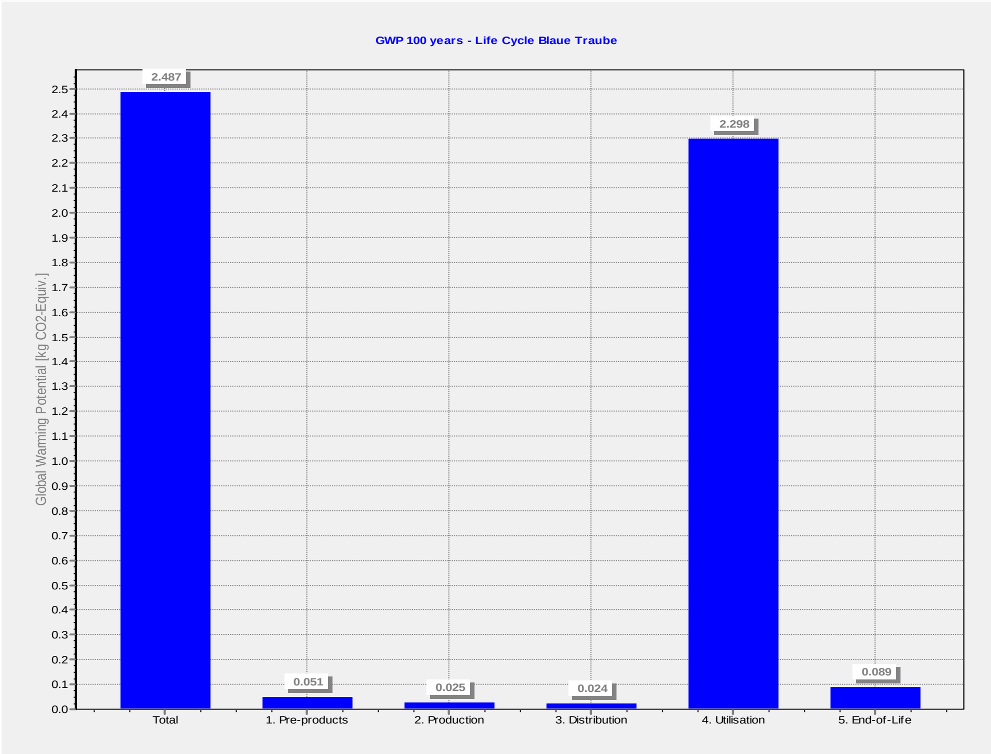

Figure 14: GWP of scenario , cradle-to-grave

(Source: GaBi 5)

Of course, the scenario does not consider potential modifications within other steps of the life cycle (utilisation, end-of-life). It is assumed that the processes of these steps are similar to the situation in Germany.

5.3.1.1.2 Results of scenario 2

The substitution of sodium sulphate by solar salt reduces the carbon footprint at about 0.022 kg CO2-e (-0.9 %) compared to the basic case.

The total carbon footprint within scenario 2 is 2.444 kg CO2-e.

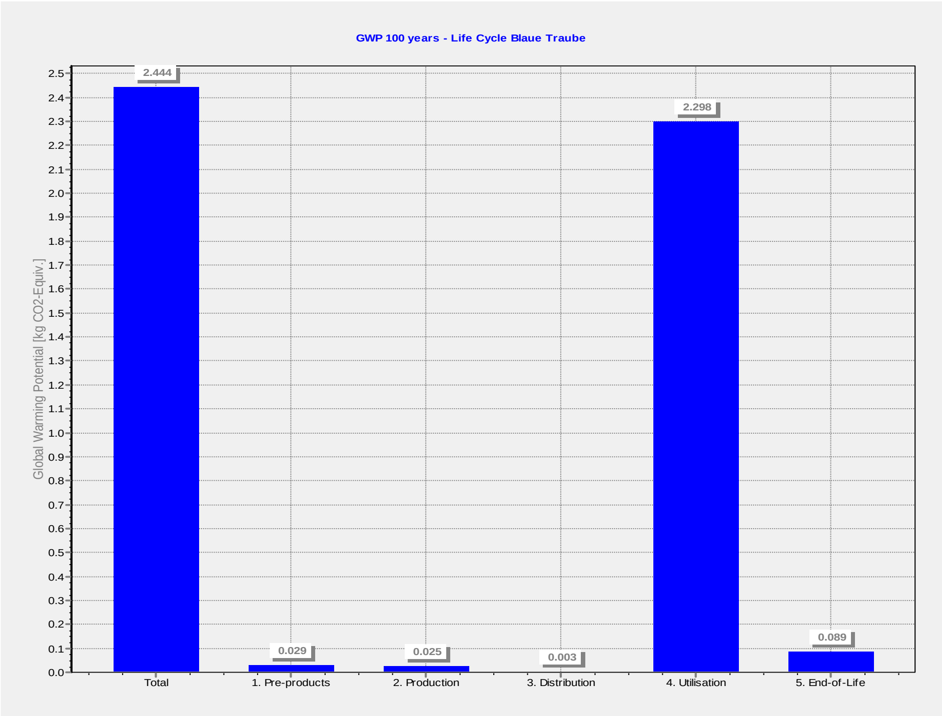

Figure 15: GWP of scenario 2, cradle-to-grave
(Source: GaBi 5)

5.3.1.1.3 Results of scenario 3-a

Using pellet heating instead of natural gas for the tap water of the bathtub decreases the total carbon footprint about 72.8 % (comparing to the basic case). The total footprint amounts to 0.671 kg CO2-e.

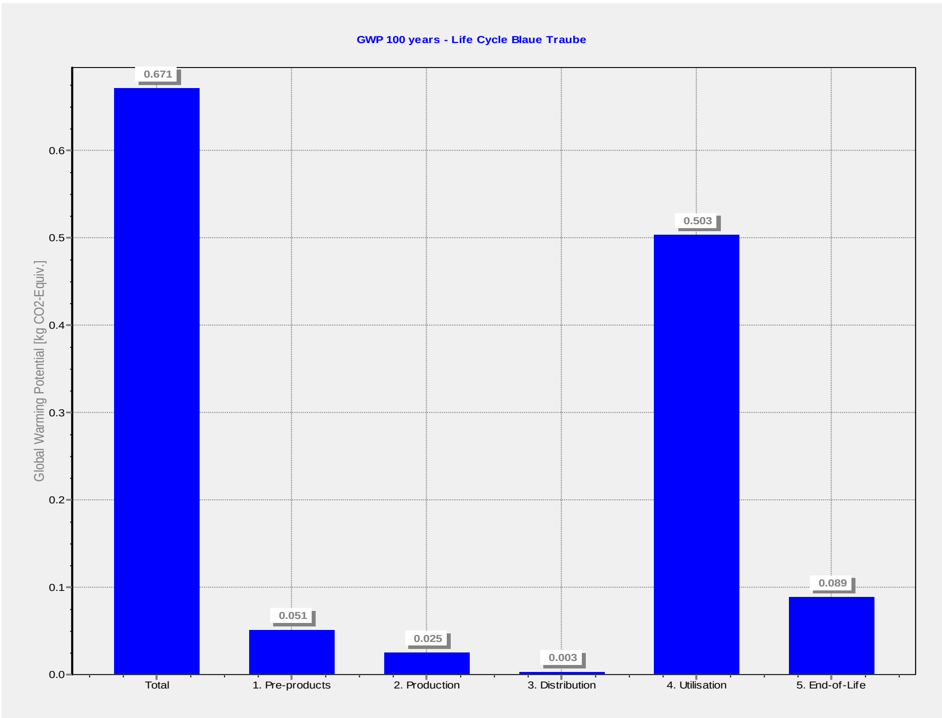

Figure 16: GWP of scenario 3a, cradle-to-grave
(Source: GaBi 5)

The impact of other life cycle steps proportionately increases (pre-products 7.6 %; production 3.8 %; distribution 0.4 %; end-of-life 13.2 %). However the dominant step is still utilisation with a rate of 75 % of the carbon footprint.

The reason of this change is the usage of wood pellets. Burning wood, as a renewable resource, is regarded as largely climate neutral process. It is assumed that the emission of carbon dioxide is equal to the absorption during the growth of the tree. With other words, the emissions are considered as a part of the natural CO2 cycle. It should be mentioned, that only a sustainably managed forest could be the foundation of using wood pellets.

Currently, pellet heating does not yet play such an important role like natural gas. The rate on energy sources to warm water in Austrian households in 2009/ 2010 was 1.3 %.[124] Hence, the potential of reducing the greenhouse gas emissions by one bath in a bathtub seems to be quite high.

[124] Cf. STATISTIK AUSTRIA (Ed.) (2011)

5.3.1.1.4 Results of scenario 3-b

The combined use of solar heat and natural gas in a multi-family house reduces the carbon footprint about 0.44 kg CO2-e (-17.8 %) compared to the solely use of natural gas.

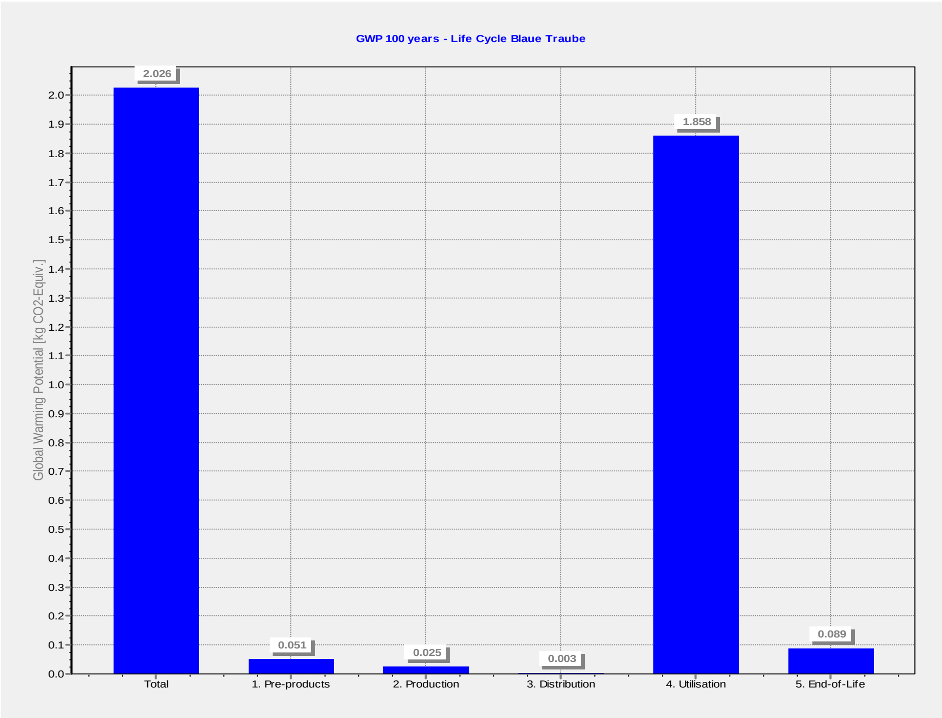

Figure 17: GWP of scenario 3b, cradle-to-grave

(Source: GaBi 5)

The ratio of solar heat on the warming of water in Austrian households was 6.7 % during the years 2009 and 2010. In general, in central European countries solar collectors need additional energy sources to ensure the supply of warm water during clouded days. Hence, the introduced scenario may be more significant than the 6.7 % hypothesize.

5.3.1.2 Uncertainty analysis

To determine the total variation of the carbon footprint Monte Carlo simulation is carried out with GaBi 5. The software separately performs the simulation for input and output flows. Also GaBi does not calculate the common 0.025- and 0.975-quantiles of the output probability distribution to specify the range, within 95 % of all values are located. Thus, to determine the total variation of the overall footprint it is necessary to edit the results of GaBi supplementary.

Table x illustrates the result of Monte Carlo simulation with 10000 runs with GaBi. Thereby the CO2-equivalents are illustrated for input and output flows of the system. The carbon footprint is the difference between outputs and inputs. Also the 0.1- and 0.9-quantiles of the overall distribution can be calculated by subtraction of the corresponding quantiles of inputs and outputs.

Knowing these values and assuming that the simulation by 10000 runs is sufficient, it is possible to calculate the standard deviation of the overall distribution and further approximate the

0.025- and 0.975-quantiles. All simulated distributions are normal or approximately normal distributions. Hence the following equation is applied to calculate the demanded quantiles.

Equation 5-19

$$Q_p[X] = \mu + \Phi^{-1}(p)\sigma, \qquad 0 < p < 1$$

Regarding the slight skew of the simulated distribution, the 0.025- and 0.975-quantiles of the total probability distributions are calculated by slightly different standard deviations. The used standard deviation depends on the adjoining 0.1-quantile and the respectively 0.9-quantile.

Equation 5-20

$$Q_{0.975}[X] = \mu + 1.96 * (Q_{0.9}[X] - \mu)/1.285$$

Equation 5-21

$$Q_{0.025}[X] = \mu - 1.96 * (Q_{0.1}[X] - \mu)/(-1.285)$$

Table 27: Uncertainty analysis, cradle-to.grave

Scenario	***Flows***	***Mean in kg CO2-e***	***Standard deviation***	***0.025-quantile in kg CO2-e***	***0.1-quantile in kg CO2-e***	***Median in kg CO2-e***	***0.9-quantile in kg CO2-e***	***0.975-quantile in kg CO2-e***
Basic case	Inputs	0.0288	3.76 %	N/A	0.0274	0.0288	0.0302	N/A
	Outputs	2.5	20 %	N/A	1.86	2.47	3.18	N/A
	Total	2.4712		1.497	1.833	2.4412	3.145	3.5063
Scenario 1	Inputs	0.029	3.77 %	N/A	0.0275	0.0289	0.0303	N/A
	Outputs	2.52	20 %	N/A	1.89	2.49	3.22	N/A
	Total	2.491		1.532	1.863	2.461	3.19	3.557
Scenario 2	Inputs	0.0283	3.8 %	N/A	0.0269	0.0283	0.0297	N/A
	Outputs	2.49	20 %	N/A	1.86	2.46	3.18	N/A
	Total	2.4617		1.5029	1.8331	2.4317	3.1503	3.51
Scenario 3-a	Inputs	3.52	22 %	N/A	2.53	3.47	4.59	N/A
	Outputs	4.19	21 %	N/A	3.06	4.14	5.4	N/A
	Total	0.67		0.4566	0.53	0.67	0.81	0.8835
Scenario 3-b	Inputs	0.0292	3.95 %	N/A	0.0276	0.0291	0.0307	N/A
	Outputs	2.06	19.5 %	N/A	1.55	2.04	2.6	N/A
	Total	2.0308		1.2553	1.5224	2.0109	2.5693	2.85217

(Own illustration.)

All results of the uncertainty analysis of each scenario are illustrated in figure 18 on the next page.

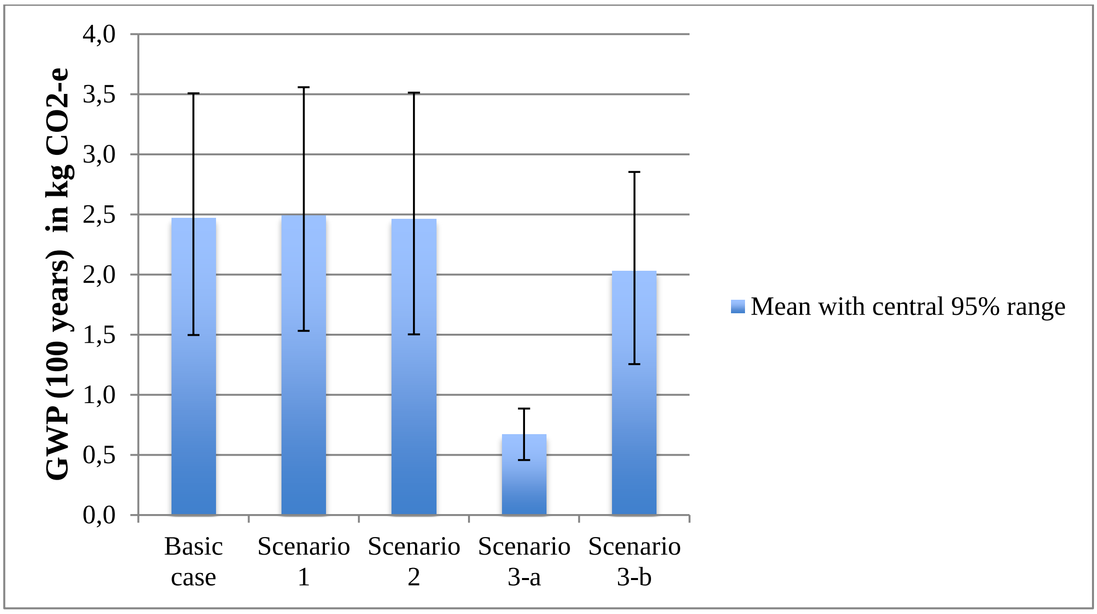

Figure 18: Uncertainty analysis, cradle-to-grave

(Own illustration.)

The use of pellet heating (scenario 3-a) always delivers the best result. The combined heating system of solar and gas (scenario 3-b) can be seen as the second best scenario. However, in some cases it is possible that the basic case is equal or even better than this scenario. This is visible by the 95% ranges.

The different transport assumption (scenario 1) as well as the use of the alternative base A instead of base A (scenario 2) do not change the result significantly.

5.3.1.3 Uncertainty importance analysis

To understand the behaviour of the several unit processes according to variability and data quality an uncertainty importance analysis is carried out. Therefore the methodology of chapter 4.3 is applied.

The influence of the considered variation of parameters on the total carbon footprint is determined by Monte Carlo simulation (1000 runs) for each parameter, keeping constant the other parameters. Data quality of unit processes is expressed by aggregated DQIs. The information about variability and data quality of each parameter is taken from the LCI (chapter 5.2).

Due to the separate display of simulation results of input and output flows within GaBi, the analysis is carried out basing on the simulation results of output flows. These results come as close as possible to the distribution of the carbon footprint.

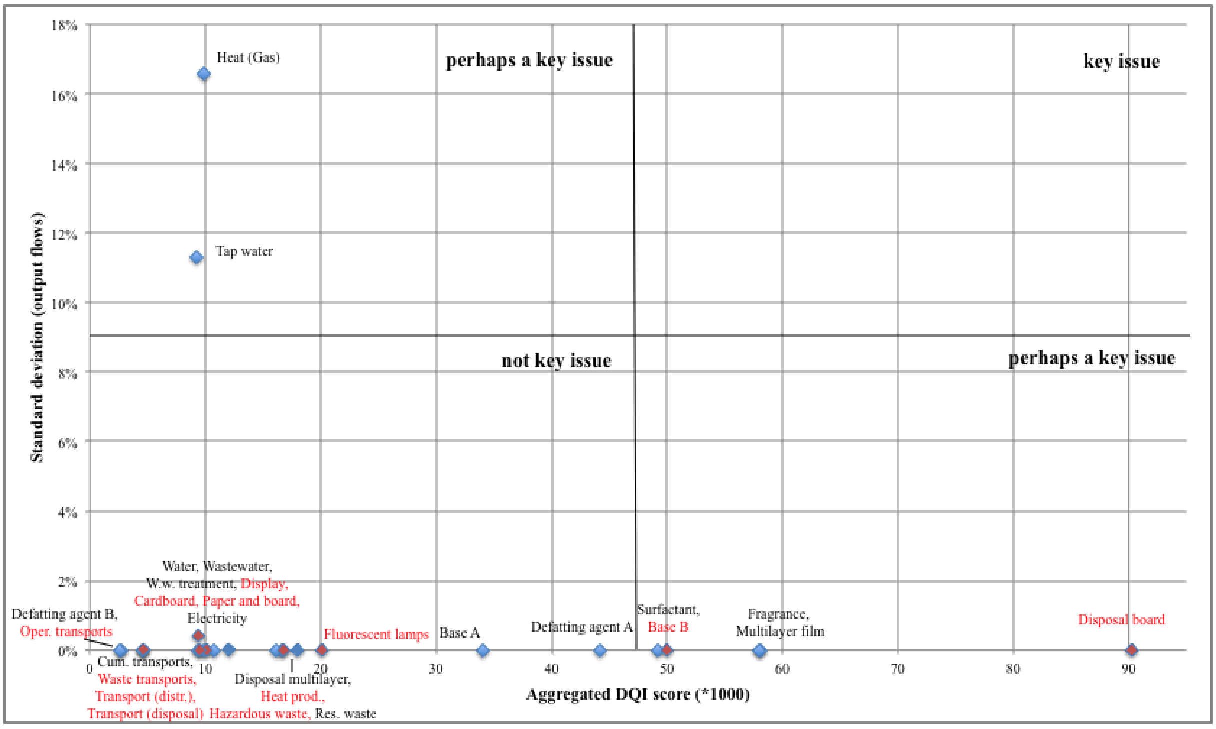

Figure 19: Uncertainty importance analysis, basic case, cradle-to-grave
(Own illustration.)

The figure illustrates the results of the uncertainty importance analysis of the basic case. The x-axis represents the aggregated DQI scores of the considered processes within the model. To get a vivid value the scores are multiplied by 1000. The y-axis shows the impact on the overall variation (expressed by the standard deviation), when varying the analysed process. Thereby all other processes are kept constant. To make visible the influence of each process on the model´s overall uncertainty the chart is divided into four commensurate areas. Finally it is possible to evaluate each process according to its impact on the overall variability uncertainty of the carbon footprint and its uncertainty according to data quality aspects. A process, which contains both types of uncertainty in a largely manner, would be a key issue. Key issues should be avoided. Being a key issue means, that the process has a high impact on the variability of the carbon footprint and on the uncertainty due to its background data.

The basic case does not include key issues. The most significant process on variability uncertainty of the footprint is heating the tap water from 10°C to 38°C. This is caused by the high variation of the assumed energy demand (5.2 – 11.2 kWh per 160 litres) and the associated greenhouse gas emissions. In contrast, the background data of this process is considered as quite good. The aggregated DQI score (multiplied by 1000) of this process is about 10. The most uncertain process according to background data is the disposal of the cardboard box and the display (DQI score 90). The impact of this process on the carbon footprint and its variation is low. The high impact of tap water on variability uncertainty is caused by the relation to the heating process. The necessary energy demand depends on the amount of tap water (120-200 litres). The more water is filled in the bathtub the merrier energy is required.

Within the chart, red processes illustrate, that there is no information about variability uncertainty available.

Illustrating the uncertainty importance analysis for scenario 1 would not deliver other results. This is caused in the insignificant change of the total footprint. Also the aggregated DQI scores of ship transport (9.3) and road transport (4.65) are low and can be seen as good documented processes with an adequate reliability. Also scenario 2 results in slight deviations within the area *not a key issue* and is not illustrated by a chart.

Scenario 3-a delivers the following results.

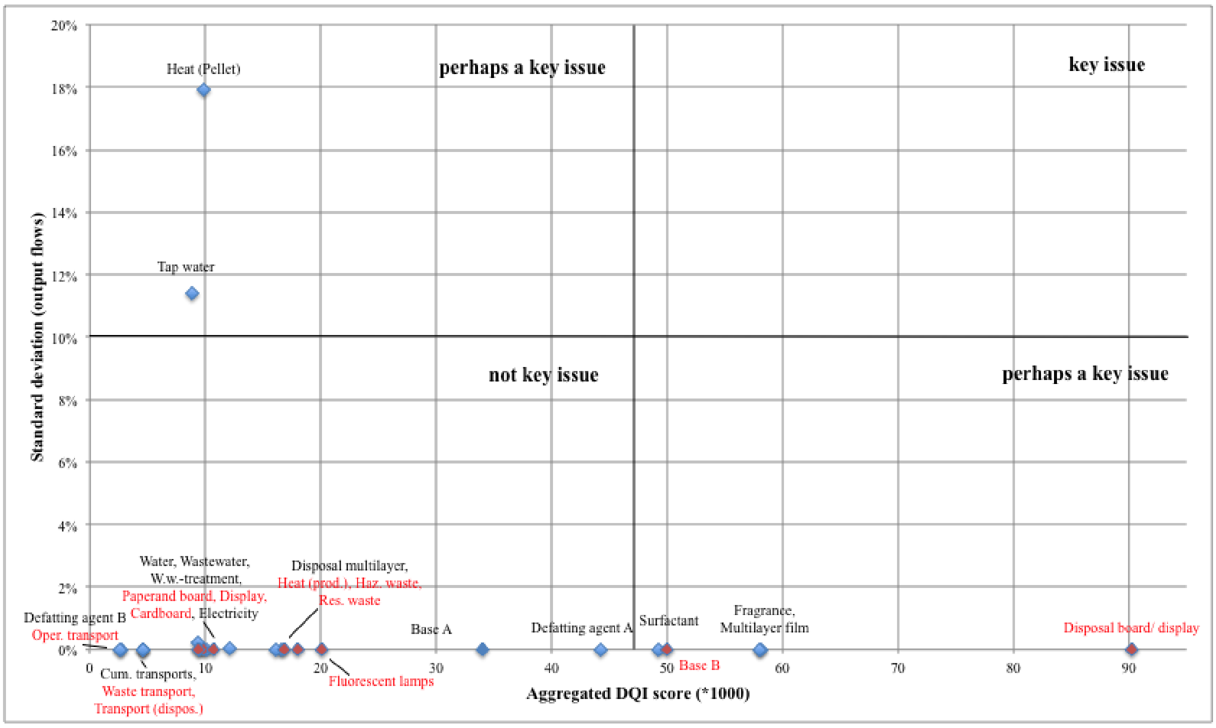

Figure 20: Uncertainty importance analysis, scenario 3a, cradle-to-grave

(Own illustration.)

Heating the tap water is still the predominant process. The substitution of natural gas by wood pellets does not change this circumstance. Background data of pellet heating is evaluated with an approximate DQI score of about 10 like heating with natural gas.

The combined use of natural gas and solar heat (scenario 3-b) delivers equal results. The heating process of tap water is approximate to scenario 3-a and all other processes are situated in the same alignment.

5.3.2 Cradle-to-gate

Utilisation is the crucial phase when considering the whole life cycle. Within this phase a high potential of decreasing greenhouse gas emissions is given. Li-iL GmbH has no direct influence on taping the full potential. The company bears the whole responsibility for the first phases of the life cycle pre-products and production. To determine the potential reduction sources, which can be realised with less effort, a cradle-to-gate analysis is carried out.

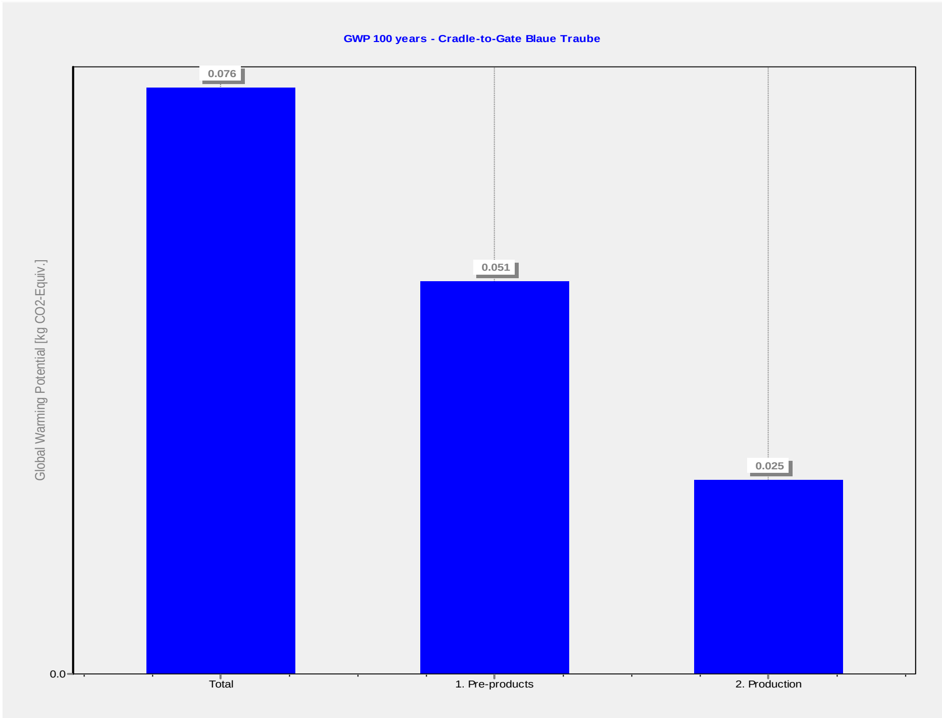

Figure 21: GWP of basic case, cradle-to-gate

(Source: GaBi 5)

The carbon footprint of producing one 60g package of bath powder BT and its packaging materials is 0.076 kg CO2-e.

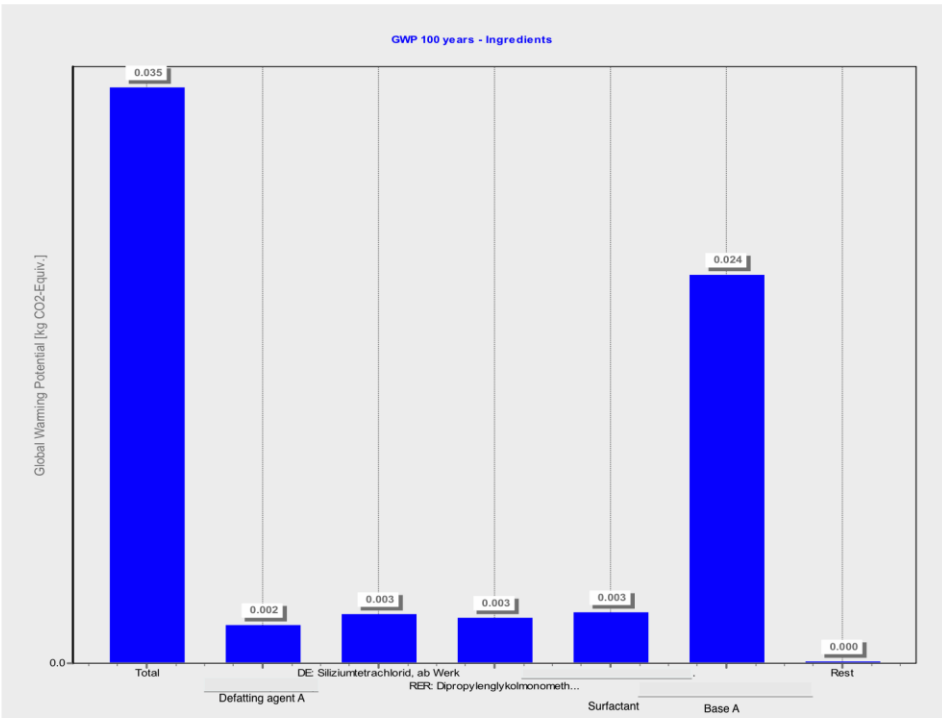

Figure 22: GWP of ingredients

(Source: GaBi 5)

Ingredients of the powder contribute with 0.035 kg CO2-e (46 %) to the total footprint. The most important ingredient is base A. The ratio of base A to the total carbon footprint (cradle-to-gate) is 31.5 %.

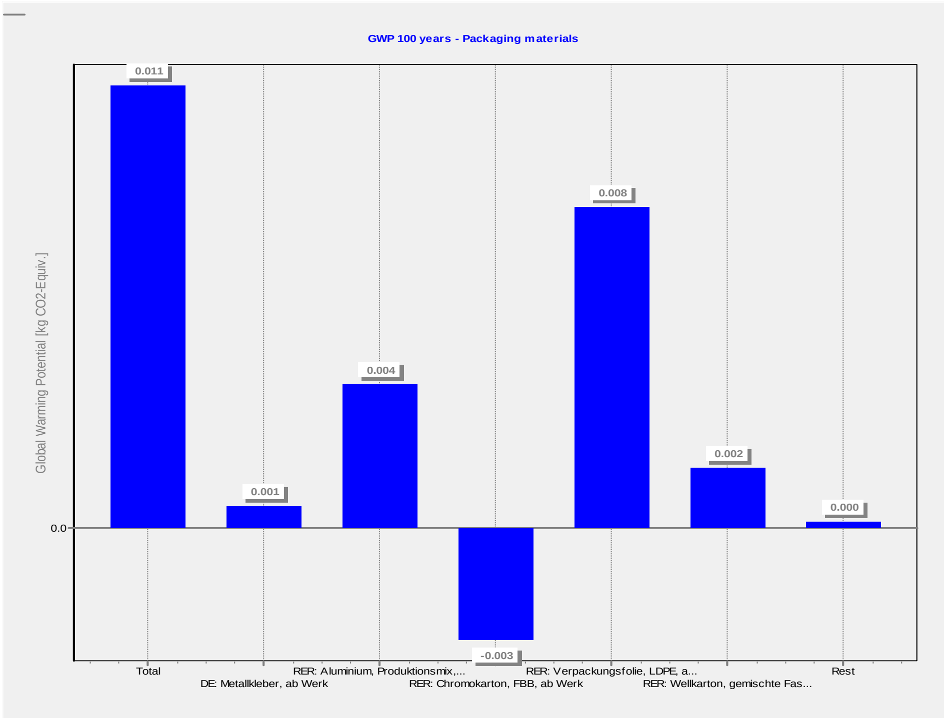

Figure 23: GWP of packaging materials
(Source GaBi 5)

Packaging materials contribute with 0.011 kg CO2-e (14.5 %) to the total footprint. Thereby the components PETP layer and PE-LD layer ("RER: Verpackungsfolie LDPE), glue ("DE: Metallkleber") and aluminium layer ("RER: Aluminium") can be merged to determine the impact of the multilayer film. The amount of 0.013 kg CO2-e (17 %) arises when adding the three illustrated processes.

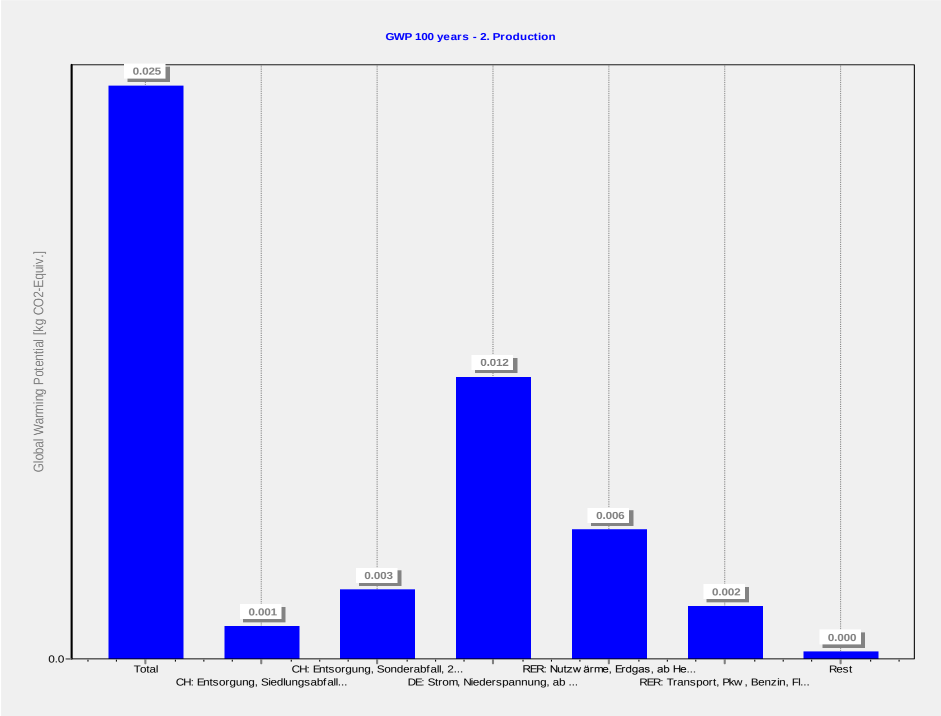

Figure 24: GWP of production, scenario 2

(Source: GaBi 5)

The impact of the production at the factory of Li-iL GmbH is illustrated in figure 24. Electricity consumption ("DE: Strom, Niederspannung") accounts for the footprint by an amount of 0.012 kg CO2-e (15.8 %).

5.3.2.1 Scenario analysis

Instead of using base A it is possible to produce the Blaue Traube powder by the usage of an alternative base A. To analyse the differences of the carbon footprint scenario 2 is used. This scenario is already touched on in the cradle-to-grave consideration, where it has just a little reduction potential of about 1 %. However, at the second glance small amounts can as well contribute to significant decrease of greenhouse gas emissions, regarding the averaged produced amount of 58000 Blaue Traube packages per month in the end of 2011.

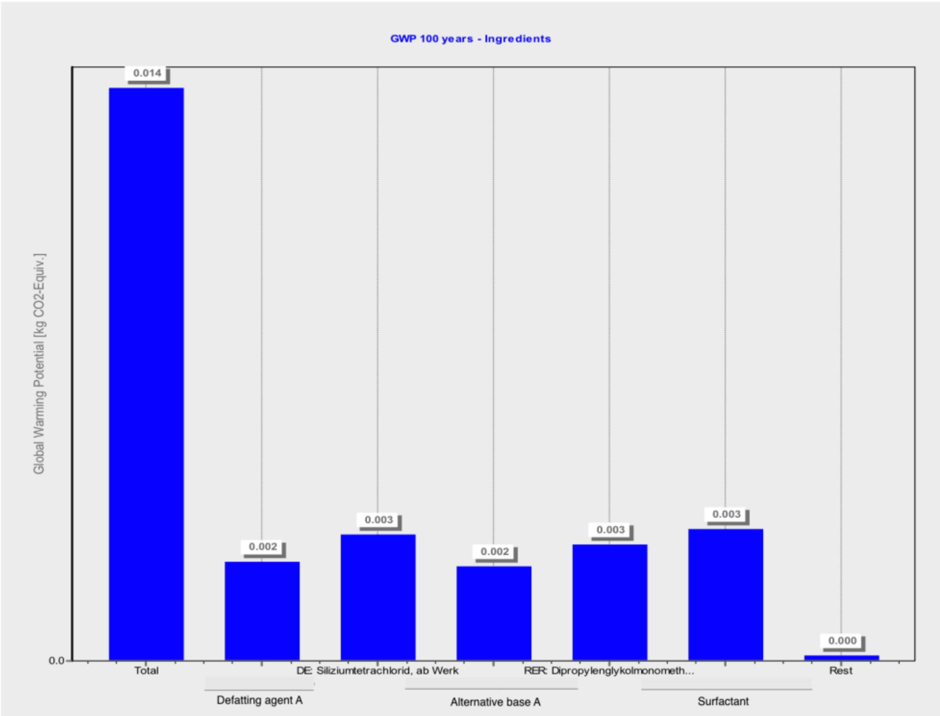

Figure 25: GWP of ingredients, scenario 2

(Source: GaBi 5)

Within the ingredients the impact is reduced by 0.022 kg CO2-e (-91.7 %). Imply the increased transport capacity to deliver the salt from France to the factory in Dresden (Germany) a total reduction potential of 0.007 kg CO2-e (-9.2 %) per package remains.

5.3.2.2 Uncertainty analysis

The analysis within the cradle-to-gate consideration is carried out in just as within the cradle-to-grave consideration. The following table includes the intermediate steps and the total 95 % range (0.025-quantile and 0.975-quantile).

Table 28: Uncertainty analysis, cradle-to-gate

Scenario	***Flows***	***Mean in kg CO2-e***	***Standard deviation***	***0.025-quantile in kg CO2-e***	***0.1-quantile in kg CO2-e***	***Median in kg CO2-e***	***0.9-quantile in kg CO2-e***	***0.975-quantile in kg CO2-e***
Basic case	Inputs	0.0203	0.248 %	N/A	0.0202	0.0203	0.0203	N/A
	Outputs	0.0965	0.672 %	N/A	0.0956	0.0965	0.0973	N/A
	Total	0.0762		0.075	0.0754	0.0762	0.077	0.0774
Scenario 2	Inputs	0.0198	0.240 %	N/A	0.0197	0.0198	0.0198	N/A
	Outputs	0.0884	1.45 %	N/A	0.0867	0.0885	0.0901	N/A
	Total	0.0686		0.0662	0.067	0.0687	0.0703	0.0712

(Own illustration.)

The result of this analysis is visualised in figure 26.

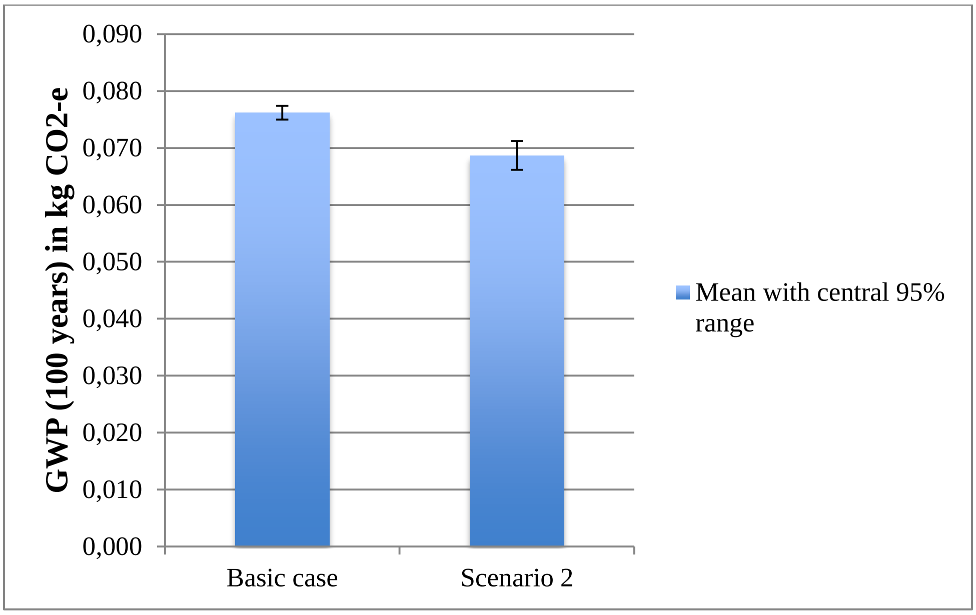

Figure 26: Uncertainty analysis, cradle-to-gate
(Own illustration.)

The basic case (production with base A) has always the higher impact on climate change than scenario 2 (production with alternative base A). The 95 % range of scenario 2 is larger than the range of the basic case, but they do not overlap.

5.3.2.3 Uncertainty importance analysis

Carrying out uncertainty importance analysis for the basic case the following chart is obtained.

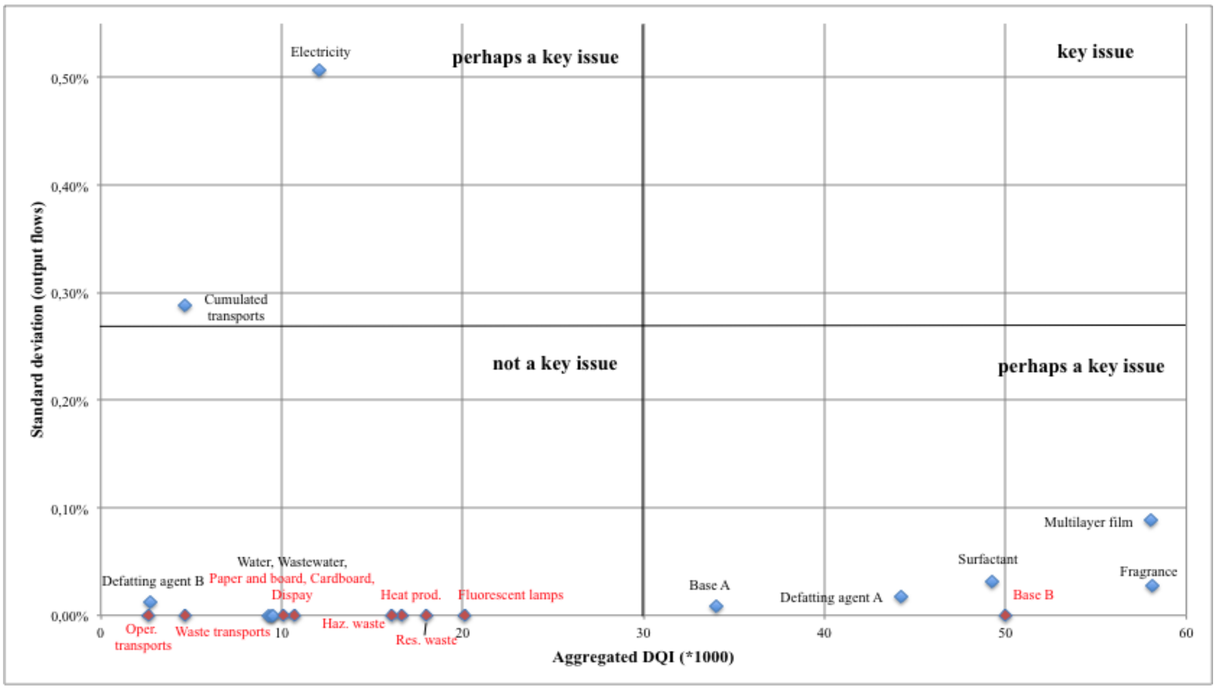

Figure 27: Uncertainty importance analysis, basic case, cradle-to-gate
(Own illustration.)

It is visible that electricity (to produce one 60g package within the factory) and cumulated transports (to deliver the pre-products to the factory) are the most important processes according to variability uncertainty of the footprint. Several pre-products are evaluated to have a minor reliability according to data quality (right lower area). No process contains both attributes, which can be interpreted as a good property of the analysed system.

The analysis of scenario 2 is illustrated in figure 28 on the following page.

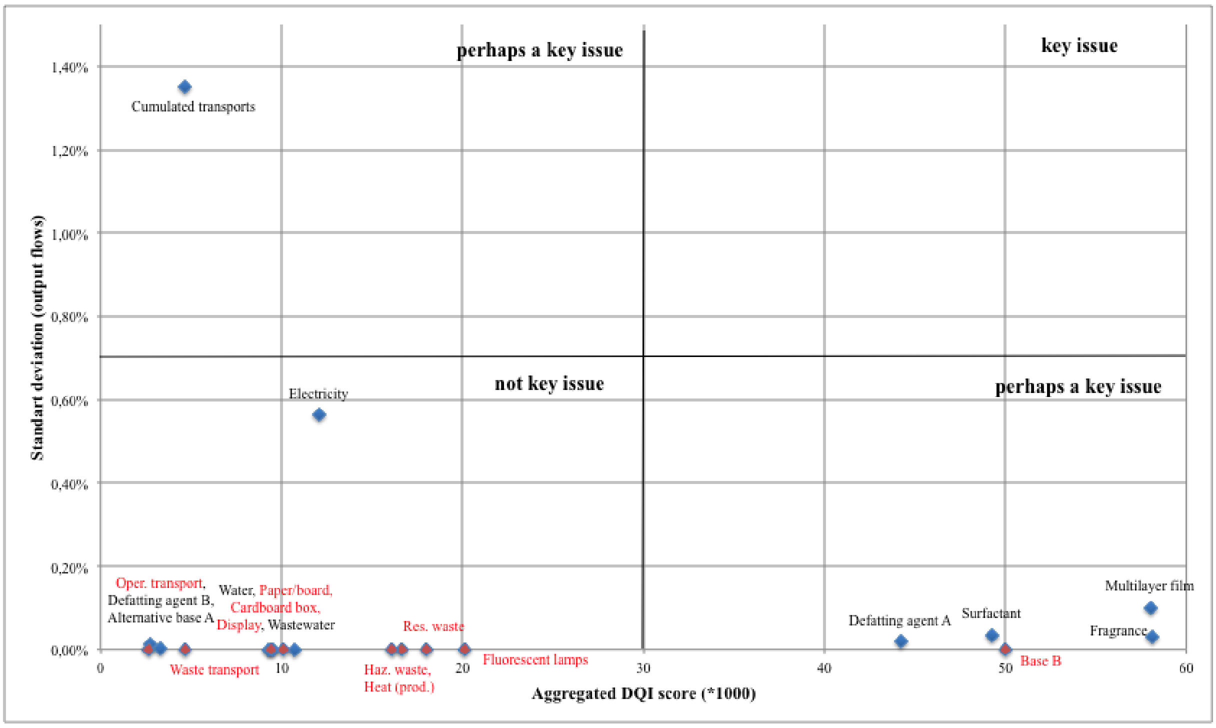

Figure 28: Uncertainty importance analysis, scenario 2, cradle-to-gate (Own illustration.)

Comparing both charts it is visible that the processes *cumulated transports* and *electricity* interchanged their positions according to variability uncertainty of the carbon footprints. In scenario 2 the importance of transports (from production sites to Li-iL GmbH) increase. Electricity consumption within the factory becomes *not a key issue*. Within the basic case electricity takes the predominant position of variability uncertainty.

The aspects of data quality do not change in a significant manner. The background data of multilayer film, fragrance, base B, surfactant and defatting agent A can be evaluated as most critical. However, it can be assumed that these processes do not have a significant influence on the overall footprint. The basis for this assumption is of course a minimum requirement of representative of the used data from the ecoinvent database and literature sources.

5.4 Interpretation und summary

Considering the whole life cycle (cradle-to-grave) of bath powder Blaue Traube the carbon footprint of the product varies between 0.5 and 3.5 kg CO2-e. The result primary depends on the system of warm water supply within the utilisation of the bath powder. Warming the tap water is the most important process within the life cycle. It contributes about 75 to 93 % to the total footprint. A pellet heating system achieves the best results of the analysed heating systems (0.5-0.9 kg CO2-e). However, the most probable value is to find between 2 and 2.5 kg CO2-e, assuming that heating with gas is a more common process in households.

The change of assumptions of the transport distance to deliver it to shops does not significantly change the result. Enlarging the transport to Japan, the carbon footprint increases about 1%, compared to a transport within Germany.

Also the choice of solar salt as the basis of the bath powder Blaue Traube only results in a decrease of the footprint by about 1 %, considering the whole life cycle.

Considering the life cycle steps to produce the bath powder Blaue Traube (cradle-to-gate), it may be an interesting advisement to substitute base A by the alternative base A. Thereby the potential of reducing the footprint is about 9 %. Even if the substitution of base A only reduces the footprint by 1 % over the whole life cycle, it may be a contribution, which is easily realisable.

The author is the opinion that the reliability of the result meets the requirements of the ISO-guidelines. The results consider the variability uncertainty, different assumptions (scenarios) as well as the quality of the used data. Uncertainty importance analysis does not determine critical unit processes (key issues). All processes, which significantly contribute to the carbon footprint, are based on representative data. The total variability uncertainty may be slightly increased by the neglecting of correlations between the unit processes tap water and heating of tap water, when carrying out Monte Carlo simulation.

A comparison with other products shall help to evaluate the product carbon footprint (cradle-to grave) of bath powder BT, which has a total range between 0.5- 3.5 kg CO2-e and a most probable range between 2- 2.5 kg CO2-e. Within the PCF Pilot Project Germany[125] carbon footprints of several products are determined over the whole life cycle. The following three example products shall be picked out. *The first example* is a 500g meal of FRoSTA.[126] The analysed impact on climate change of frozen tagliatelle with wild salmon varies between 1.2 and 3.9 kg CO2-e.

The second example is a package of 10 toilet paper roles.[127] The calculated carbon footprint is 2.5 kg CO2-e of the complete package. The usage phase is not considered within the analysis.

The third example is the application of Schauma shampoo from Henkel as part of taking a shower.[128] The carbon footprint varies between 0.185 and 0.380 kg CO2-e. Within the study warming the water is the most important process. The total carbon footprint is strongly affected by temperature of water and its amount. Hence the results of this shampoo correlates with the analysed bath powder Blaue Traube.

In conclusion, the study only detects the impact on climate change. To give recommendations, which regard other environmental impacts, additional analysis is necessary.

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[125] Cf, THEMA1 GmbH (Ed.) (2012)
[126] Cf. FROSTA AG; PCF PILOTPROJEKT DEUTSCHLAND (Eds.) (2009)
[127] Cf. DM-DROGERIE MARKT GMBH & CO. KG; PCF PILOTPROJEKT DEUTSCHLAND (Eds.) (2009
[128] Cf. HENKEL AG & CO. KG; PCF PILOTPROJEKT DEUTSCHLAND (Eds.) (2009)

6 Conclusion and outlook

The thesis illustrates types and sources of uncertainties within life cycle assessment, which are currently discussed in the LCA community. Furthermore the methods to deal with these uncertainties are described. Thereby the most important types are variability and knowledge uncertainty within the LCI phase.

The most common and adequate method is uncertainty analysis with Monte Carlo simulation. The requirements of this method are discussed and room of improvement is illustrated. Especially the generation of probability distributions within the ecoinvent database is assessed as not optimal. The distributions should only include information about variability uncertainty, without using data quality indicators to enlarge the percentile-ranges. The main problem of merging DQIs into probability distributions is the contemptuousness of the importance of random sampling. An inappropriate sample will always deliver an inappropriate mean.

Basing on the discussed problems, a method is introduced to avoid the problematic merging of variability uncertainty and data uncertainty to generate probability distributions. The introduced uncertainty importance analysis allows a consistent differentiation of these types of uncertainty. Furthermore an assessment of the used data of LCA studies is possible.

The method is applied at a PCF study of the bath powder Blaue Traube of Li-iL GmbH. Thereby the analysis is carried out over the whole life cycle (cradle-to-grave) as well as cradle-to-gate. The study gives a practical example to the company determining the carbon footprint of products. In addition, it meets the requirements of ISO guidelines of publishing the study and comparing it with other products.

Within the PCF study the introduced method allows a differentiation of variability uncertainty and data uncertainty. The included uncertainty importance analysis supports the assessment of each aggregated unit process within the analysed product system. Finally this analysis can provide a basis to collect additional, more reliable or uncertain data for critical processes.

However, the PCF study discloses several problem areas, which appeared when using the method. The first area is *practicability*. Carrying out Monte Carlo simulation, several software tools are available in connection with LCA. The study within this thesis is carried out with the help of GaBi 5. This software performs the simulation for input and output flows separately. That means additional effort is necessary to determine the total variation of the result. Also the introduced uncertainty importance analysis can only carried out in a circuitous manner. Each unit process, which contains variation of its needed amount, has to be analysed separately. Thereby the Monte Carlo simulation of 1000 runs is performed for each parameter separately. Analysing 16 unit processes and 4 scenarios, 64 Monte Carlo simulations have to be carried out. A relief could be produced, by integrating the formula of Geisler (page 23) into matrix based LCA software. It might be, that other LCA software already uses such algorithm to calculate the contribution to variance. Within GaBi 5 no such an algorithm exists. If there would be an algorithm, it would be less time intensive to carry out the analysis.

The second problem area is the *completeness* of the introduced uncertainty importance analysis. The analysis postulates the assignment of variability ranges to each process. Within the study it is possible, that not all processes have such a range (e.g. figure 19, page 61, red processes). Especially when allocating data to processes, a problem may result. If an allocation procedure do not deliver variability ranges, it might be better to assume an appropriate range. Even though the analysed processes with no variability within the PCF study do not have such a significant contribution to the carbon footprint, it is generally possible to contribute significantly to the footprint significantly without variability.

The third problem area is the *reliability* of the factors of DQIs (page 35). It is not possible to improve the reliability of these values, which are taken from ecoinvent. At some points a discussion may be usefully. An interesting point of view is the treatment of the indicator temporal correlation as a reduction of the mean (page 16-17). Thereby the mean of the random variable (e.g. energy demand) is reduced by a specific percentage rate.

Summarised the thesis shall contribute to the comprehension of uncertainties in LCA and identify methods to increase the reliability of its results. Furthermore linguistic uncertainty shall be reduced, by explaining the concepts of uncertainty (error) propagation and other statistical concepts (confidence interval vs. quantile range).

The basis of LCA and in particular the basis to determine the impact on climate change is physical knowledge about the natural processes. Future studies could consider the uncertainty of such parameters (e.g. CO2-e) to distinguish between emissions (e.g. methane vs. nitrous oxide). Based on the fact that this knowledge contains uncertainty as well, the following citation of Frank H. Knight shall close the thesis.

"You cannot be certain about uncertainty."

Appendix

Table 29: Search strings and results of literature research (pp.74-75)

Search string	Number of entries (# relevant)						
	Google scholar	EBSCOhost	Econbiz	Emerald	ScienceDirect	SpringerLink	TEMA
Topic 1: Uncertainties general							
(ökobilanz OR oekobilanz OR life cycle assessment* OR LCA OR ecobalance) AND (uncert* OR unsicherheit OR variab*) AND (review OR meta analysis OR overview OR survey)	148000 (1)	105 (14)	28 (0)	42 (2)	6181 (19)	2142 (14)	4 (0)
Topic 2: Parameter uncertainty							
(ökobilanz OR oekobilanz OR "life cycle assessment" OR LCA OR ecobalance) AND (parameter OR data AND (uncertainty OR unsicherheit OR variability)	19200 (4)	80 (4)	46 (3)	143 (0)	185 (6)	155 (29)	-
Topic 3: Scenario uncertainty							
(ökobilanz OR oekobilanz OR "life cycle assessment" OR LCA OR ecobalance) AND (scenario AND (uncertainty OR unsicherheit OR variability))	8690 (17)	82 (2)	(0)	-	30 (8)	31 (3)	-
Topic 5: Cosmetic industry							
(ökobilanz OR "life cycle assessment" OR LCA OR "carbon footprint" OR "co2 fußabdruck") AND (cosmetic OR Kosmetik)	2000 (2)	25 (3)	-	-	259 (6)	160 (1)	-
Topic 6: Carbon Footprint							
("carbon footprint" OR CF OR "Global Warming Potential" OR GWP OR PCF OR Fußabdruck) AND (uncertainty OR unsicherheit OR variability OR Variabilität)	11 (2)	283 (2)	-	1139 (0)	235 (6)	33 (4)	-

											Total
Wiley	WISO	ACS Legacy	Search AGRIS	Web of Knowledge	OSTI	ETDE	Greenfile	GreenPilot	OLS-SSG Umwelt	RAM Data-base	
144 (4)	293 (8)	128 (5)	3 (0)	326 (5)	23 (0)	810 (0)	20 (2)	3527 (1)	0 (0)	4677 (0)	62
83 (0)	-	33 (8)	-	657 (3)	-	-	-	-	-	-	50
18 (2)	-	176 (7)	-	90 (0)	-	-	-	-	-	-	33
48 (0)	-	12 (6)	-	-	-	-	-	-	-	-	15
231 (0)	-	12 (0)	-	955 (2)	-	-	-	-	-	-	16

(Own illustration.)

17 analysed LCA studies:

ACHTEN, W.M.J.; VANDENBEMPT, P.; ALMEIDA, J.; MATHIJS, E.; MUYS, B. (2010): Life Cycle Assessment of a Palm Oil System with Simultaneous Production of Biodiesel and Cooking Oil in Cameroon. In: Environmental Science and Technology, 44, 2010, pp. 4809-4815

BOJARSKI, A.D.; GUILLEN-GOSALBEZ, G.; JIMENEZ, L.; ESPUNA, A.; PUIGJANER, L. (2008): Life Cycle Assessment Coupled with Process Simulation under Uncertainty for Reduced Impact: Application to Phosphoric Acid Production. In: Ind. Eng. Chem. Res., 47, 2008, pp. 8286-8300

CORDELLA, M.; TUGNOLI, A.; SPADONI, G.; SANTARELLI, F.; ZANGRADO, T. (2008): LCA of Italian Lager Beer. In: International Journal of Life Cycle Assessment, 13, 2008, 2, pp. 133-139

DE KONING, A.; SCHOWANEK, D.; DEWEALE, J.; WEISBROD, A.; GUINEE, J. (2010): Uncertainties in a carbon footprint model for detergents; quantifying the confidence in a comparative result. In: International Journal of Life Cycle Assessment, 15, pp. 79-89

FLYSJÖ, A.; HENRIKSSON, M.; CEDERBERG, C.; LEDGARD, S.; ENGLUND, J.E. (2010): The impact of various parameters on the carbon footprint of milk production in New Zealand and Sweden. In: Agricultural Systems, 104, 2011, pp. 459-469

HUMBERT, S.; ROSSI, V.; MARGNI, M.; JOLLIET, O.; LOERINCIK, Y. (2009): Life cycle assessment of two baby food packaging alternatives: glass jars vs. plastic pots. In: International Journal of Life Cycle Assessment, 14, 2009, pp. 95- 106

LANGEVIN, B.; BASSET-MENS, C.; LARDON, L. (2010): Inclusion of the variability of diffuse pollutions in LCA for agriculture: the case of slurry application techniques. In: Journal of Cleaner Production, 18, 2010, pp. 747-755

LUCAS, A.; SILVA, C.A.; NETO, R.C. (2011): Life cycle analysis of energy supply infrastructure for conventional and electric vehicles. In: Energy Policy, accepted 2011

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Table 30: Uncertainty importance analysis, all scenarios, cradle-to-grave (pp.78-79)

Parameter	Scenario									
	Basic case		Scenario1		Scenario 2		Scenario 3-a		Scenario 3-b	
	Aggr. DQI score (*1000)	SD (output) in %	Aggr. DQI score (*1000)	SD (output) in %	Aggr. DQI score (*1000)	SD (output) in %	Aggr. DQI score (*1000)	SD (output) in %	Aggr. DQI score (*1000)	SD (output) in %
Defatting agent A	44.2	0.00067	44.2	0.00067	44.2	0.00067	44.2	0.0004	44.2	0.0004
Defatting agent B	2.7	0.000495	2.7	0.000495	2.7	0.000495	2.7	0.0003	2.7	0.0003
Surfactant	49.25	0.0012	49.25	0.0012	49.25	0.0012	49.25	0.0007	49.25	0.0007
Base A	34	0.00037	34	0.00037			34	0.0	34	0.0
Alternative base A					3.3	0.00003				
Fragrance	58.1	0.0001	58.1	0.0001	58.1	0.0001	58.1	0.0006	58.1	0.0006
Multilayer film	58	0.0034	58	0.0034	58	0.0034	58	0.002	58	0.002
Cum. Transports	4.65	0.0111	4.65	0.0111	4.65	0.0475	4.65	0.0068	4.65	0.0068
Electricity	12.05	0.0191	12.05	0.0191	12.05	0.0191	12.05	0.0111	12.05	0.0111
Water (prod.)	9.85	0.0	9.85	0.0	9.85	0.0	9.85	0.0	9.85	0.0
Wastewater (prod.)	9.4	0.0	9.4	0.0	9.4	0.0	9.4	0.0	9.4	0.0
Tap water	9.83	11.3	9.83	11.3	9.83	11.3	9.83	11.4	9.83	11.4
Heat (bath)	9.23	16.6	9.23	16.6	9.23	16.6	8.8	17.9	5.3	16.1
Wastewater treatment	9.4	0.406	9.4	0.406	9.4	0.406	9.4	0.24	9.4	0.24
Multilayer Disposal	16.8	0.0012	16.8	0.0012	16.8	0.0012	16.8	0.0007	16.8	0.0007
Base B	50	-	50	-	50	-	50	-	50	-
Display	10.7	-	10.7	-	10.7	-	10.7	-	10.7	-
Cardboard box	10.1	-	10.1	-	10.1	-	10.1	-	10.1	-
Heat (production)	16.65	-	16.65	-	16.65	-	16.65	-	16.65	-
Res. waste	18	-	18	-	18	-	18	-	18	-
Paper and board	9.5	-	9.5	-	9.5	-	9.5	-	9.5	-
Fluorescent lamps	20.1	-	20.1	-	20.1	-	20.1	-	20.1	-
Hazardous waste	16.1	-	16.1	-	16.1	-	16.1	-	16.1	-
Operational transports	2.65	-	2.65	-	2.65	-	2.65	-	2.65	-
Waste transports	4.65	-	4.65	-	4.65	-	4.65	-	4.65	-
Transport (distribution)	4.65	-	4.65	-	4.65	-	4.65	-	4.65	-

Ship transport (distr.)			9.3	-						
Disposal board	90.25	-	90.25	-	90.25	-	90.25	-	90.25	-

(Own illustration.)

Table 31: Uncertainty importance analysis, cradle to gate

Parameter	Scenario			
	Basic case		Scenario2	
	Aggr. DQI score (*1000)	SD (out-put) in %	Aggr. DQI score (*1000)	SD (out-put) in %
Defatting agent A	44.2	0.018	44.2	0.0187
Defatting agent B	2.7	0.0124	2.7	0.0142
Surfactant	49.25	0.0309	49.25	0.0344
Base A	34	0.0089		
Alternative base A			3.3	0.0009
Fragrance	58.1	0.0278	58.1	0.03
Multilayer film	58	0.088	58	0.1
Cum. Transports	4.65	0.288	4.65	1.35
Electricity	12.05	0.507	12.05	0.563
Water (prod.)	9.85	0.0001	9.85	0.0001
Wastewater (prod.)	9.4	0.0001	9.4	0.0002
Base B	50	-	50	-
Display	10.7	-	10.7	-
Cardboard box	10.1	-	10.1	-
Heat (production)	16.65	-	16.65	-
Res. waste	18	-	18	-
Paper and board	9.5	-	9.5	-
Fluorescent lamps	20.1	-	20.1	-
Hazardous waste	16.1	-	16.1	-
Operational transports	2.65	-	2.65	-
Waste transports	4.65	-	4.65	-

(Own illustration.)

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Abstract

The following thesis deals with methods to increase the reliability of the results in life cycle assessment. The paper is divided into two parts. The first part points out the typologies and sources of uncertainty in LCA and summarises the existing methods dealing with it. The methods are critically discussed and pros and cons are contrasted. Within the second part a case study is carried out. This study calculates the carbon footprint of a cosmetic product of Li-iL GmbH. Thereby the whole life cycle of the powder bath Blaue Traube is analysed. To increase the reliability of the result a procedure, derived from the first part, is applied. Recommendations to enhance the product´s sustainability are then given to the decision-makers of the company. Finally the applied procedure for dealing with uncertainty in LCAs is evaluated.

The aims of the thesis are to make a contribution to the understanding of uncertainty in life cycle assessment and to deal with it in a more consistent manner. As well, the carbon footprint of the powder bath shall be based on appropriate assumptions and shall consider occurring uncertainties.

Basing on discussed problems, a method is introduced to avoid the problematic merging of variability uncertainty and data uncertainty to generate probability distributions. The introduced uncertainty importance analysis allows a consistent differentiation of these types of uncertainty. Furthermore an assessment of the used data of LCA studies is possible.

The method is applied at a PCF study of the bath powder Blaue Traube of Li-iL GmbH. Thereby the analysis is carried out over the whole life cycle (cradle-to-grave) as well as cradle-to-gate. The study gives a practical example to the company determining the carbon footprint of products. In addition, it meets the requirements of ISO guidelines of publishing the study and comparing it with other products.

Within the PCF study the introduced method allows a differentiation of variability uncertainty and knowledge uncertainty. The included uncertainty importance analysis supports the assessment of each aggregated unit process within the analysed product system. Finally this analysis can provide a basis to collect additional, more reliable or uncertain data for critical processes.

Keywords: Uncertainty, knowledge uncertainty, variability uncertainty, analysis, Monte Carlo simulation, LCA, PCF

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