LCA, A TOOL TO STAY?

A SEARCH FOR CRITICAL FACTORS INFLUENCING THE RELIABILITY AND USE OF LIFE CYCLE ASSESSMENTS

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ABSTRACT

The negative impact human economic activity has on the environment has proven to be significant. A product or service can have an impact on many categories such as toxicity, acidification, or CO₂. To reduce this negative impact, and avoid it reaching critical levels, companies and governments must make informed decisions. To make these, Decision Support Tools (DST) have been developed. There are many kinds of decision support tools out there. An example of such a tool is a Life Cycle Assessment (LCA). This approach is based on a hardscience perspective, providing quantified impacts of a product, accumulated in a set of impact categories. Although researchers often take utmost care to use precise data and derive the best conclusions, the method is subject to flaws. These flaws are widely discussed in literature. There is however a lack of studies that research the reliability and use of the LCA methodology beyond research. In this research, the author has looked at the reliability and use of the LCA methodology, both looking at the research and the implementation phase. The research question is therefore: "Which factors influence the reliability and use of the LCA methodology?" From the literature analysis and interviews, it became clear that there are still some major weaknesses within the methodology. The factors found to play a role in the reliability and use of LCAs are communication issues, comparability, uncertainty and assumptions, relative importance, data availability, objectivity, temporal and geographical limitations, time and quality tradeoff, the gap between academic and applied research, quality, impact category issues, market effects, cutoff issues, and allocation issues.

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1. INTRODUCTION TO LIFE CYCLE ASSESSMENTS AND RESEARCH QUESTION

In this chapter I will introduce the Life Cycle Assessment (LCA) methodology, the research gap and aim, and the research questions.

1.1 INTRODUCTION

Our growing production and consumption patterns cause a continuously increasing pressure on the environment. To protect the environment, we are implementing changes into our production methods to achieve more sustainable development. Consumers and producers increasingly demand sustainability to be a considered aspect within their products and services. From producers this requires the implementation of innovations within their production cycles. Additionally, sustainability reporting is the way they communicate their performance to the world. This creates transparency for consumers as well as other market parties, allowing for competition within sustainability. This inevitably leads to some taking advantage in the form of green washing – making a product appear more sustainable without it actually being so – but the initial intent is that it leads to quantifiable improvements.

DECISION SUPPORT TOOLS

There are several ways to assess the sustainable value of a product. In literature, these assessment methods are called decision support tools (DSTs) or decision-support systems. There are many examples of such tools or systems, one can think of Cleaner Production, Corporate Citizenship, Corporate Social Responsibility, Design for Environment, Eco-efficiency, Eco-labeling, Environmental Management Systems, Environmental Social Accounting, Factor X, Green Chemistry, Industrial Ecology, Sustainable Livelihoods, or Sustainability Reporting and indeed Life Cycle Assessment (LCA) (Lozano, 2015). Some are concepts rather than methodologies, and some fill a specific niche. However, it is clear that if an organization wants to improve their activities on an environmental level they have a lot of possibilities. Apart from corporate initiatives, there are also tools that are closely related to government standards. In literature, a much used example of this is the Environmental Impact Assessment (EIA). EIA has been designed to cover and compare all aspects of a project on a sustainable level (Arts et al., 2015; Runhaar, 2008; Runhaar & Driessen, 2012). A new form of EIA is Strategic Environmental Assessment, where social and economic considerations are part of the EIA (Chaker et al, 2005).

DSTs are those tools that help people managing an organization in making the right decisions. Different ones, such as the ones listed above, are often highlighting different parts of the bigger elephant in the room. The choice for one or the other method is therefore a managerial choice, and is of subjective nature. Additionally, choices do not necessarily exclude other choices. Baitz et al. (2012) argue that these tools are often "a tool in a toolbox", and that for instance risk assessment can complement impact analysis. There is a myriad of specifically

designed tools for different cases to be found (see e.g. Beier et al, 2007; den Boer et al, 2007; Gupta & Palsule-Desai, 2011; Halide et al, 2009; Kicherer et al, 2007; Sharma et al, 2005; Welp, 2000; Wiek & Binder, 2005; Yuan et al, 2005). They are often an adaptation of one of the methods mentioned earlier, resulting in an even wider range and a jungle of methodologies. This makes comparison between DSTs challenging as they serve different purposes with different rational choices underlying the decisions. The science-policy interface is the way science interacts with decision makers. DSTs are a crucial part of the science-policy interface of sustainability as they are the developed tools that science has presented to the world. They are the proposed solution to a problem. Although they are constantly subject to further research, adaptation, and improvement, they are being implemented today. This observation means that whatever their shortcomings are, their effects are measurable. A quick literature search on DSTs will show that LCA is a widely measured, used and discussed tool (see e.g. Christensen et al, 2007; Morris, 2005). Below I will further discuss this methodology.

LIFE CYCLE ASSESSMENT

LCA is based on the presumptions of empirical-rational decision making (Rowley et al, 2009). The methodology has its roots in the 1980s, when sustainability thinking grew and people started to gather information on the emissions of the production and use of resources. This information was structured, and now ISO provides the most widely used standards for measuring impacts in LCA. In 2001, UNEP/SETAC embarked on an initiative to further determine the future role of LCAs and to determine what best practices are. Additionally, the European Union is now looked at LCA-based methodology to provide environmental product information. These decisions are necessary because, as mentioned before, in LCA a lot of choices are made which lead to the inclusion of subjective values of an assessment. These choices must be backed up by solid argumentation, but inevitably remain subjective in nature. Still today, LCA is under construction, but also used widely already. There are many deviations from the standard method of LCA. Think of for instance the inclusion of social aspects in social LCA (sLCA). The exclusion of this factor is a widespread criticism in conventional LCA (Guinée et al., 2011). One can think of Life Cycle Costing (LCC) too, where financial parameters are added to LCA (Gluch & Baumann, 2004; Kicherer et al., 2007). Basically, LCA, sLCA, and LCC form the pillars of thinking of sustainability: planet, people, profit. All these different tools and subgroups of LCA hint towards conflicting interests between different pillars. These conflicting interests must all be taken into consideration by the users of LCA, and different parameters are valued differently in the final decision.

LCA is of growing importance in organizations with regard to sustainability to justify choices made within the organization. Organizations are increasingly willing to invest in improving their performance on a sustainability level, and are applying a wide range of DSTs for this. LCA is one such DST that has been presented by research groups and can be highly descriptive and detailed. LCAs are designed to quantify product impacts, and to then choose the most sustainable one based on different indicators, which are called impact categories. This will allow for precise and effective management of resources within a company in order to improve on a sustainable level. In analyzing the environmental impact of a product or service, LCA considers the full life cycle. An LCA can theoretically be about any product, from coffee machines to bananas to steel beams. Additionally, an LCA can be conducted over specific aspects of a product such as fuel use, packaging, or transport. Every part of the production process of a product should be mapped closely and is the subject of careful analysis. This means it is not limited to for instance just water use or carbon footprinting. Presumably because of its practical applicability and rationality, scholars are increasingly interested in LCA (Baitz et al., 2012). This is supported by a steady increase in scholarly articles, currently peaking at around 1800 on Scopus in 2014.

A typical LCA consists of four steps: the goal and scope definition, the life cycle inventory, the impact assessment, and the interpretation phase. In the goal and scope definition, the exact boundaries of the system are defined. This category consists of four main parts: firstly, the functional unit, which is the exact definition of what is being studied. Additionally, researchers define the system boundaries, the assumptions, and the limitations. Another part in this phase is the allocation of environmental burden, when the environmental impact of a product is due to different factors in the production process. Lastly, the relevant impact categories are chosen: the categories where the product has the most significant impact. Examples of these are toxicity, acidification, or CO_2 emissions. In the second phase, the life cycle inventory, the researcher compiles an inventory of all the flows flowing from nature to the product system and back. This means material as well as energy use, but also the emissions back into nature. This is typically displayed in a flow chart displaying all activities along the line. As a third step, the impact assessment is done, which means that the flows from step two are evaluated and any significant impacts are assigned to the impact categories, using impact equivalents. This is a standardization method, and it will be discussed below. The final interpretation phase leads to the conclusions which should include the identification of significant issues, the evaluation of the study and the recommendations.

Standardization is an important aspect of LCA, as it allows for comparison of potentially harmful substances with different impacts. The choice, method and numbers behind standardization have been revised throughout the years. The LCA methodology has been improved and its range of impact categories have been expanded. The choice of database for comparison and measurement is also one that should be taken into consideration before starting an LCA, adding subjective value to the research. An example is the one I mentioned earlier and which is used most widely, the ISO database.

By having introduced LCA, the scientific community wanted to fix the issue of not knowing the direct impacts of products. They have developed a DST that can quantify impacts and provide a rational choice for decision makers when choosing between different product or service options with a significant environmental impact, which was a direct result of growing environmental concerns within and outside the scientific community. LCA was the answer to the demand for whole-scale quantifiable measurement tools.

KNOWLEDGE GAP

LCA is a hard science tool that attempts to provide a clear picture of a product or service's impact on the environment but it is also prone to flaws. Some of these flaws have been widely discussed in literature, others have been largely neglected (Baitz et al., 2012; Baumann & Tilman, 2004; Guinée et al., 2004; Reap et al., 2008). The latter is especially true for the postresearch implementation phase of an LCA. There is a gap in academic knowledge concerning the factors that influence the effectiveness of LCA in the final stages of decision making. This directly influences the reliability and usefulness of the methodology. With this thesis I want to uncover these factors and provide recommendations so that academics and other users of LCA can start looking at the methodology as an integrative picture of both hard science and subjective values. The ultimate goal is to provide knowledge on how to improve the usefulness of the LCA methodology.

This thesis will have its relevance first and foremost as an academic research to find out the difficulties of LCA in practice, which is a knowledge gap in current scientific literature. It is by no means a quantitative study showing the exact impacts of LCA as a tool in decision-making processes. Rather, the research is on identifying the factors that influence reliability and use of LCA. By unraveling these problems I want to make recommendations for both academics and practitioners. Academics can use the information gathered in this thesis to gain a deeper understanding in the development and the methodology of LCAs. Additionally, it might serve as a wakeup call that, when developing a comprehensive method such as LCA from a scientific point of view it might not work out as intended in practice. Secondly, this research can serve practitioners of LCA because it reflects the impact of their use of LCA. The expert accounts in this thesis could provide insight into the difficulties LCA practitioners have, and proposes a list of aspects to be aware of before doing an LCA.

1.2 RESEARCH QUESTION

To find an answer to the knowledge gap described in the introduction, I will ask the following research question:

WHICH FACTORS INFLUENCE THE RELIABILITY AND USE OF THE LCA METHODOLOGY?

Factors can be any weakness that is inherent to the LCA methodology. I deliberately chose to present these as factors and not to try to quantify them. In this way I can still present major points for improvement of the methodology and tread into detail about them. This include the much researched methodological factors, as well as issues after the research phase, in the implementation phase. The reliability part of the main research question specifically focuses on the research phase. The use part focuses on the phase after the research. Despite the fact that the two parts are discussed as different ones here, there is of course overlap.

The research framework provides a visual representation of the steps needed to answer this question (Figure 1). This research framework shows my line of thought and the assumptions I made along the way. These assumptions of course influence the final outcomes. Starting from the top, the focus lies on a more general and broader perspective of the importance of environmental considerations. Decisions that are known to affect the environment are often made with decision support tools. Additionally, there is an increasing trend in awareness of these environmental issues, which means DSTs are used more often and therefore need to be as effective as they can be. The literature and report review on LCA comes together into insights into the reliability and use of LCA as a decision support tool.

I had the choice to either base an interview on the literature results, or make them open interviews. I chose the latter because then participants can provide points that stem from their own expertise, rather than reciting the points that I found in the literature. I will then compare the independent interview factors with the literature factors, to locate consistencies or inconsistencies between the two, and come up with the final list of factors which is the answer to the main question of this research. Additionally, I will provide recommendations for academics and practical users of LCA. Below I present the sub-questions based on the research framework.



Figure 1. Research framework.

There are five sub-questions to find the answer to the main research question. These flow are based on the steps in the research framework. First I want to find out the general characteristics of LCA to get an idea on how literature uses the methodology and how they write about it. This is important because the factors that influence reliability and use will have an effect on these general characteristics.

1. WHAT ARE THE GENERAL CHARACTERISTICS OF LCA ACCORDING TO LITERATURE?

I will then look at the literature I found, and define the factors that influence reliability and use of LCA according to literature, and after that according to experts.

2. WHICH FACTORS INFLUENCE THE RELIABILITY AND USE OF LCA ACCORDING TO LITERATURE? 3. WHICH FACTORS INFLUENCE THE RELIABILITY AND USE OF LCA ACCORDING TO EXPERTS?

When I have the results of the interviews I can combine these and analyze them in order to come up with the final list of factors that defines the weaknesses of LCA methodology in practice.

4. WHAT ARE THE KEY DIFFERENCES AND SIMILARITIES BETWEEN FACTORS FOUND IN LITERATURE AND THOSE MENTIONED BY EXPERTS?

I will then provide recommendations for improvement based on the findings in the literature and interviews.

5. HOW CAN THE LCA METHODOLOGY BE FURTHER IMPROVED?

RESEARCH OUTLINE

These questions will form the backbone of my research. After answering them, I was able to answer the central research question as well as provide useful recommendations for revision or improvement of LCA. To structure the research, I will start with presenting my research approach in chapter 3. Then, in chapter 4, I will give a more detailed account of the research objects, which consist of both literature research and expert interviews. After this, in chapter 5, I will do a literature analysis, followed by the expert interview analysis in chapter 6. Chapter 7 will analyze and compare the data found in the previous two chapters, and provide the recommendations for practical use of the information. Then, in chapter 8, I will reflect on the methodology, the research process, possible limitations, and provide recommendations for further research. Chapter 9 will be the conclusion.

2. RESEARCH APPROACH

The methodology of a research project largely determines the type of outcome. Quantitative data suggests higher statistical relevance if acquired correctly. This comes with the downside of not always having enough resources and time to collect this data. The research question too, does not always require this type of data. Qualitative data encompasses data that is not statistically relevant, but provides much more detailed insight into a topic. This research is based on the latter.

Data was collected in two ways. Firstly, through the literature review I have identified the main characteristics and weaknesses. This is an important first step as it provides insight into the current academic debate. Using a simple tags for C (Characteristics) and W (Weaknesses) which were used to highlight pieces of text proved to be a clear method for categorization of results. Secondly, expert interviews provided additional insight and

information from people with hands-on experience. These were conducted in an open way. Using these two types of methods, this research presents an analysis of both academic and reallife experience, strengthening the findings. Using different types of data reveals additional information that perhaps otherwise would not have been highlighted, I can more easily recognize inconsistencies or confirmation. Literature research gives an overview of the developments through time on the subject of LCA, and forms a solid backbone for any research while interviews can confirm or contradict findings from the literature, provide deeper insight, or answer specific questions. The literature and interview data were gathered using MaxQDA with coding colors for general characteristics and weaknesses. Below I will further explain the methodology of this research.

2.1 LITERATURE RESEARCH

Literature was found using the Scopus search engine, and through two other channels which are my university network and works I have collected doing coursework. The total list of used literature for the analysis can be found in Appendix 2. I looked for publications and used keywords such as *decision support tools* (and its variations), *sustainability, life cycle assessment* (and its variations), and, in combinations with the others, *effectiveness, reliability, and use*. A quick search using these terms leads to a wide array of publications and requires sorting and selecting. Firstly, I looked at the number of citations. Although arguably this does filter out some relevant newer papers, it also shows the top used papers on the topic. To compensate for higher number of citations in older publications, I also filtered a second time on year of publication. Lastly, having taken courses on LCA and decision support tools, the university has provided me with useful sources that could not have been found using Scopus. The final count of the analysis is thirty-seven literature sources, of which thirty-one provided useful insights for this research. The authors and titles will be further discussed at the start of the literature research chapter.

In the literature research I highlighted pieces of useful information in the sources as characteristics, or weaknesses. This was done in order to partially answer the sub questions. The general characteristics were used to support this thesis, and to provide a backbone for the weaknesses. This serves to provide the reader with a way to put the weak points into perspective by gaining insight into the methodology. Secondly, the weaknesses were compiled into a single database without classification. After that, they were classified using an iterative and deductive process in factors. Each time I found a new weakness I tried to place them into an existing category, thereby constantly reviewing categories and trying to narrow down categories, without simplifying too much. If I could not fit them into an existing category, a new category was born. The open interviews have been put together after the literature review. Because of the open nature of the interviews, no specific points found in the literature were included in the, although of course the interviewees could come up with these themselves and present similar points to the literature studies. My goal was to let the participants present their own points, and only later find out if these match with the literature or not. It is solely about finding new or confirming factors that influence the reliability or use of LCA. Arguably, presenting points from the literature could have given me additional confirmation or not. However, because the participants were experts in the field, who work with LCAs on a daily basis, I found it more valuable to acquire input during an interview.

I have emailed every participant a copy of the summary of their interview as it will be presented in this thesis, to validate the findings and make sure they agree with what I write down. Additionally, I have asked for feedback from the participants on the quality of the interview. I have chosen to contact as many as possible scholars, governmental institutions and companies for the interviews. Of course not everybody replied with equal enthusiasm. This makes for a colorful and seemingly random sample of interviewees. The selection criteria were not very strict because of the limited time and contacts to my disposal, as long as they were working with LCA in their daily activities, or have worked extensively on one in the past. Below is a list of participants and their backgrounds concerning LCA.

Adam Brundage, Adidas. Adam Brundage is a contact found via Dr. Krishna Manda. He currently holds the position of program manager for product sustainability at Adidas. At Adidas he used LCA to research the product sustainability of fibers used for footwear and apparel. He quantifies these resources, and also takes part in the communication phase of LCA. For this research, he enthusiastically provided information about the application of LCA in a real-life case.

Anne Gaasbeek, Pré Sustainability. Pré Sustainability are the developers of one of the most widely used LCA computing tool, SimaPro. Additionally, they provide consulting in the field of LCA and sustainability. Anne Gaasbeek works at Pré and helps organizations with implementing sustainability. Her job has a special focus on the user perspective, which is a large part of the main question of this thesis.

Diederik Schowanek, Procter & Gamble. Originally trained as a bioengineer, Diederik Schowanek eventually became the leader of the LCA team within Procter & Gamble. Currently he is working with risk assessment of chemical substances, and the implementation of different sustainability tools including LCA. He is of particular interest for this research because he specifically focusses on the implementation and communication of the tools. **Flavie Lowres, BRE Group**. Flavie Lowres works at BRE Group, originally a public company that was set up to develop industry standards for building. Nowadays she is involved in setting up these standards through LCA. She can provide an expert view on what it is like to work with a growing LCA industry, and to tackle potential big problems the methodology has.

Geanne van Arkel, Interface. I came in contact with Geanne van Arkel through Krishna Manda, who recommended I should talk to her about LCA. She currently works at Interface as head of the sustainability department. She does not perform LCAs, but works with implementing the outcomes of the tool. Interface is a company that specializes in carpeting. She looks at the ecological as well as the social impacts in the company, as well as outside the company.

Jeroen Guinée, Leiden University. Jeroen Guinée works at Leiden University with a focus on LCA and substance flow analysis. For this research he was of particular importance because of his long track record in the field of LCA, and because of his contribution to an important piece of work in this field. Together with other scholars he wrote the "Handbook on Life Cycle Assessment. Operational Guide to the ISO standards" is a tool widely used for basing LCAs on (Leiden University, 2015).

Krishna Manda, Utrecht University. Dr. Krishna Manda works for Lenzing, a sustainable fiber producer, as well as working at Utrecht University. At both, he is an expert in LCA. His PhD thesis on the application of LCA for corporate sustainability focused on how the tool is used for both quantification and awareness. His work also focuses on the communication phase, which proved very useful for this thesis.

Li Shen, Universiteit Utrecht. Li Shen was one of the first I contacted for an unprepared talk about LCA and the possibility of an interview. She currently works at Utrecht University and provided me with interesting reads on her work on PET bottles. Currently she has moved on to work on other topics, but she was keen to provide me with the knowledge she had gained from her studies on LCA and PET bottles.

Niels Jonkers, IVAM. IVAM is a company that originated from the University of Amsterdam. Dr. Niels Jonkers has a background in chemistry and is currently working at IVAM. He is a senior researcher here and conducts LCA on waste management and packaging materials. He is a researcher with field experience and was very willing to discuss LCA with me for this research.

The half-hour interviews were held using a pre-made form (Appendix 1). The participants were given the option to meet face to face, over the phone, or over Skype, with a strong preference for Skype because of the ease and quickness. All interviews were eventually held over Skype. The questions are based on the main and sub questions of this thesis. Only

minor adaptations were made based on the participant's background, such as their specific expertise. The interviews were held in English or Dutch, based on the preference of the participant (Appendix 1). Oftentimes, after the introduction, a participant would keep talking and answer most of my questions by themselves before I could ask them. I allowed this, as they would provide information I would otherwise have trouble finding out. Additionally, as long as I made sure that in the end every question was answered, the interviews would end up complete. The open nature of the interviews provided a wide range of insights.

Before any interview I briefly introduced myself and asked if I could record them, additionally I took notes during the interviews. Below is a description of the questions I asked to stimulate the participants to talk about the weaknesses of LCA. Firstly, I asked the participants to introduce themselves. I had of course found out about their company and their background as well as I could by using the internet, but they might tell me something here that I should be aware of. This proved to be especially useful because they would tell me about their present projects and interests. Then, I immediately wanted to jump onto the weaknesses, which formed the body of most of our interviews. This one question alone kept most participants talking for a while, and provided me with ample usable data. After that, I asked about some personal experience with LCA in terms of projects, which often provided illustrations of earlier mentioned weaknesses. This sometimes presented new weaknesses the expert had not thought of before. I also wanted to know if LCA is a generally strong or weak methodology in its goal of solving environmental issues, as this is the desired effect of the method. The last important question relates to how the expert sees the future of LCA and its development. The last two questions often raised new points in terms of strengths or weaknesses, or current developments within the methodology dealing with these issues. I finished the interviews with asking if there was anything they still wanted to add, which sometimes resulted in interviews taking much longer than half an hour. I concluded with a formal question on how to refer to them in my thesis, as well as with asking whether they would want to receive a copy of the thesis.

2.3 COMPARISON

The literature and interviews have been analyzed, which led to a list of categories for each. These categories are based on an iterative and deductive process, and are an aggregation of points mentioned in either literature or interviews. They are called 'categories', and not yet 'factors', because they are still broader than the final list of factors. I have aggregated these further into a single table, which is the final list of factors that influence the effectiveness of LCA based on the findings. In an attempt to make factors equal in importance I have developed a simple method for scoring them. This score is an aggregated score based on both the literature and interviews. I have calculated the percentage of appearances of each factor in the literature and interviews separately, and then combined them. Some factors have a zero percent occurrence in either the literature or the interviews, because they were only mentioned in one of the two. By using a simple formula, the factors were scored from zero to a hundred (Formula 1).

Formula 1. Calculation of scores for each factor.

The choice for a maximum score of a hundred is based on the fact that working with percentages is easy here. This method is of course subject to limitations which I will discuss in the reflections and limitations chapter. The factor score presents the final results of my thesis, showing the relative importance of each factor found to be an issue in the LCA methodology. The factor scores will also yield the recommendations for improvement of the methodology.

3. LITERATURE RESEARCH

The final analysis, consisting of both literature papers and interview participants, will determine the outcome of my main research question. Therefore it is important to know what and who the researched literature and interview cases are, and to familiarize myself and the reader with the topic of LCA. Below I summarized the sources. Although this was done structurally, I present the information in a narrative way. This research would ever increase in validity with a larger number of cases from both sources, but as with any research I had to make a tradeoff between time and resources available to me. In total I have managed to analyze 37 papers. In this chapter I will answer the two first research questions, *What are the general characteristics of LCA according to literature?* and *Which factors influence the reliability and use of LCA according to literature?*

3.2 WHAT ARE THE KEY CHARACTERISTICS OF THE LCA METHODOLOGY?

Guinée et al. (2004) describe an LCA as an analysis of the environmental burden of products at all stages of their life cycle. This includes the extraction of resources through the production of materials, product parts and the product itself. The environmental burden is defined in impact categories such as ozone layer depletion, human toxicity or ecotoxicity. The product is measured by a pre-defined standard or quantity of itself. If a comparison is made between two or more products, a functional unit is used.

The first sub-question of this thesis is used to find out how to define an LCA by its general characteristics. Some were prevalent in all works analyzed, which I will first describe here using the more general works on LCA methodology (Baitz et al., 2012; Baumann & Tilman, 2004; Guinée et al., 2004; Reap et al., 2008). An LCA is comprised of different research phases, which are briefly discussed in the introduction. These were the goal and scope definition, the inventory analysis, the impact assessment and the interpretation phase (Reap et al., 2008). It is not within the scope of this thesis to present an elaborate overview of the methodology itself.

Although I will discuss characteristics here, and weaknesses relating to these phases later, I would recommend interested newcomers to LCA to read the *Hitchhiker's Guide to LCA* for a more a much more detailed and thorough understanding of the steps taken (Baumann & Tilman, 2004). The general characteristics here are however enough to understand the related weaknesses which will be discussed later. Note however that since 2004, there have been multiple developments and new researches in the field of LCA. In short, doing an LCA bears quite some resemblance to conducting any scientific research, starting with a goal and scope definition – including establishing the aforementioned functional unit. The inventory analysis is the data collection phase. The impact assessment is where the impacts of all the data are assigned to impact categories. And in the interpretation phase the conclusions are generated.

LCA is a tool for decision supporting and information supply (Baitz et al, 2012). There can be many reasons an organization wants to be informed about environmental impacts in their decision making. Guinée et al. (2004) tread into more detail here. Firstly, they could want to analyze the origins of problems related to a given product. These problems could for instance be increased observed environmental burdens, or a rise in production or cleaning costs. Secondly, an LCA is a very useful tool for product comparison. It allows for the unraveling of intricate aspects concerning the environmental burdens of products. When done for two or more products and compared to a baseline scenario an LCA can provide a solid basis for comparison. Thirdly, LCA can be used for new product design. And finally, LCA can compare improvements of two products, which is somewhat similar in nature to the second point, researching two new products.

I will now present a picture of the general characteristics of LCA, and how it is used in academic publications. All in all, energy and waste seem particularly interesting topics in the field of LCA. When looking through the Scopus database I found that it were these that had the highest number of citations. This could be explained by the relatively high importance of these kinds of topics, with major impacts on our environment, and ample media coverage. Additionally, governmental bodies are mostly concerned with these macro issues. General papers on the methodology were also found using Scopus, but these were much less cited. This clustering of topics is important to gain an overview of the possible bias this research can have, however, it does not further affect the research approach.

After many years of implementation of LCA there are also a vast amount of publications on this topic. From these publications I have selected ones from different years, with a special focus on a larger amount of papers from recent years to compensate for high citations in older papers. Each of them is an LCA, a paper about LCA, or a variant on it. As described in the methodology chapter, I have found them using a literature search on Scopus. The next paragraph will consist of thirty-seven small descriptions, where each work is explained with their research question or aim, their methodology, and their general conclusion. They are clustered in four topics: methodological, waste, energy, and other . Some papers have minor overlap, but the clustering is to keep the overview. Waste and energy are generally popular topics of papers on LCA, and others are Of course, summarizing a paper does not do full justice to its content, but for the sake of this research it is important to provide a brief overview of the cases to familiarize the reader with the topic. It also serves to illustrate what is being done in the field of LCA, and how the scientific community reports on this topic. Some of the literature sources have been very explicit about the four phases of LCA, others require some understanding of LCA to filter out the components, and others have not used this model so clearly. The combined overview of research into specific LCAs and the general concept of an LCA should provide a clear insight into general characteristics and weaknesses.

PAPERS ON THE LCA METHODOLOGY

From its onset, the LCA methodology has evolved and improved in significant ways. Additionally, the ISO database on which LCAs are based is under constant revision. So much so, that conclusions of older LCAs have to sometimes be significantly adjusted to account for newly found impacts. Inevitably, much has been written on the methodology. Below I present a selection of pieces with a methodological nature. They are not specifically part of an LCA, but rather focus on the improvement of the methodology as a whole. The two biggest works in this are Baitz et al. (2012) and Reap et al. 1 & 2 (2008), who provide clear overviews of the state of LCA and its weaknesses. The others focus on areas that are not covered by these, they present deviations from the method such as LCC or sLCA, but also specific areas of LCA which deserve special attention. In total, twelve general papers on LCA methodology have been used.

Baitz et al. (2012). provide an overview of some of the major assumptions that LCA is based on, as well as a discussion of some of its important weaknesses. This is mostly from a theoretical perspective, and goes deep into the technical details of the methodology from an academic point of view. It additionally looks at the viability of LCA as a business case, and whether there is added value in using it. Manda (2014) also looks at the concept of value creation; however, he is not used in the final analysis since he is included as an interview participant. Gluch, P. & H. Baumann (2004) look at LCC, which is an LCA-based method that includes financial parameters. This can be done in different ways and makes for interesting considerations for management level decision makers. This paper was useful for this thesis as it provided a broader view on LCA, and its different branches. Another work I have included on the inclusion of costs or the notion of value in LCA is Kicherer et al. (2007). They argue that environmental decision support tools and particularly eco-efficiency are becoming increasingly important. This paper looks at how to combine its two most important pillars: costs and environmental impact. This is done using a normalization method, and they conclude with a ratio methodology. Pizzol et al. (2014) severely question this methodology of including costs into LCA. They focus on whether monetizing social and biophysical aspects that are the basis of LCA is a useful method of standardizing outcomes. They categorized different methods to do this and conclude with a ranking of these methods. Next to papers on LCC, I also wanted to include a key paper on sLCA, which is another LCA-like method. I chose Jørgensen et al. (2008). It offers insight into the current position and developments into sLCA by presenting a broad literature review.

Uncertainty is an important topic in LCA. I have included two specific papers on this topic which are Geisler et al. (2005) and Huijbregts et al. (2001). In Geisler et al. (2005) the authors write in a topic editorial for uncertainties in LCA. The influence of uncertainty, they say, is studied very little so far. They showed that some impact categories show great uncertainty and therefore potentially impact the final results. They advise caution in finding significance in the results of LCA. Huijbregts et al. (2001) wrote an article for the working group at SETAC and provide an overview of the conclusions they found on data availability and quality. These are two major problems in the area of LCA. They here describe on how to assess this problem using a model. Additionally, they found that modeling uncertainty should be common practice, but it often is not.

Another major work that provides an overview is Reap et al. (2008) who, in a two-piece publication, take the reader through each of the four steps of LCA and describe fifteen major unresolved problems. This is based on a literature review, just like this study is. They call for more standardization, synchronization in methodology, and dynamic modeling. Additionally, they propose solutions to problems others have not addressed yet. A final paper on the methodology of LCA is Klinglmair et al. (2013). The authors aim to present current discussions on LCA, and to contribute to the development of more robust and understandable methods. They focus on key areas of resources and their depletion: renewability, recyclability and criticality. Their conclusions are that these areas are underdeveloped within LCA.

WASTE MANAGEMENT LCA

A rather large topic in LCA literature is waste management. Several governmental initiatives have made guidelines for waste management by companies. Companies then use LCA to find their impacts on the environment and which areas they should focus on for improvement. This explains the high level of citations by academic scholars. EASEWASTE proved to be a significant topic in my Scopus search, where LCA is adapted to develop a waste assessment tool. This standardized tool is under constant revision, but makes comparison between different waste management options possible. Christensen et al. (2007) describe their experience with the use of EASEWASTE. They focus on the technical struggles the makers came across when trying to make an adaptable decision support tool. The conclusion is that these tools can provide significant advantages to environmental decision-making. Additionally, Manfredi & Christensen (2009) compare six landfilling technologies with a focus on the influence of active operations. Here again the EASEWASTE tool is used. They conclude that there should be focus on landfill gas and leachate because that influence the environmental impact greatly. Another tool included in this literature review is LCA-IWM, which den Boer et al. (2007) write about. Their paper is a general overview of the tool, and the assumptions it was based upon.

Another major paper on waste was written by Bogner et al. (2008). The many people from IPCC who worked on this paper researched waste emissions on a European level, which form a small part of total GHG emissions globally. This paper offered an in-depth look at a

comprehensive LCA done by IPCC, and provided several insights into a large-scale LCA project. Waste is of course not only a topic in Europe. Morris (2005) conducted an LCA based on two major projects in the USA on waste. He concludes that recycling has more energy savings and lower environmental burden than either landfilling or incineration.

Finally, I included a paper by Renou et al. (2008). This article is a case study performed on a wastewater treatment plant. The authors discuss methodological issues as well as casespecific issues. They compared different methodologies and the effect on impact categories. They found significant differences in outcomes between methods in the human toxicity category.

ENERGY EFFICIENCY LCA

Energy is another important topic in LCA. There are many publications on different energy production options, especially when it comes to photovoltaic systems. Changes in materials and production technologies all have to be quantified. This is logical, since the market for these systems relies on the fact that their technology improves the state environment. Additionally, people want to know whether what they do is cost efficient, which is something that was often included in these LCAs. Sixteen papers in total were analyzed on energy topics, not all on photovoltaics.

Within energy LCA, solar energy is a big topic. There are a multitude of ways to use solar energy, and they all differ slightly. This depends on production, material use, and the use phase. Firstly, I used Ardente et al. (2005). This paper is an analysis of a solar thermal collector, but has an extensive part on uncertainties and sensitivity, which is of particular use for this paper. The authors have looked at macro applications and implications of such a technology. Espinosa et al. (2012) write about indium, a critical rare component in making solar cells. They research a replacement for this material, and its energy payback time and overall environmental impact. Pacca et al. (2007) compare two photovoltaic systems. They perform an LCA, as well as a sensitivity analysis to show how their results are influenced by uncertainties which affect the final results. In the ideal scenario, one of the systems proves to be much more effective. Four more comparisons of photovoltaic systems used for analysis are Parisi et al. (2014), Peng et al. (2013), Raugei et al. (2007), and Tripanagnostopoulos et al. (2005).

A rather interesting paper on the comparison between biofuel and PV was Geyer et al. (2013). Biofuel production is seen as a threat to food supply and natural habitats; PVs directly use sunlight for energy production. This paper compares the two methodologies of what they call sun-to-wheels energy production in terms of land use. This means that solar energy can either be used to generate power through PV, or through biomass, and that the two are competing for land area. PV performs better and also has the lowest emissions in its life cycle. Another paper on fuel efficiency is by Granovskii et al. (2006). This study compares transportation by using hydrogen or gas. They focus on energy efficiency and greenhouse gas emissions. Hydrogen fuel cells should be 25-30% more effective to be competitive with gas.

problems still, but is promising. Additionally, Granovskii et al. (2007). adapt the LCA methodology to study the exergetic, economic and environmental effectiveness of hydrogen using wind and solar energy instead of fossil fuels. They conclude that in theory, the hydrogen fuel cells are much more effective in all fields, especially the environmental ones.

Schreiber et al. (2012) look at carbon capture storage (CCS), which according to them has been thoroughly researched using LCA. In this study, the authors compare fifteen of these studies, over three technologies. They present a variety of environmental benefits created by the technology, but call for an even better understanding of the technology. Another paper on another source of energy is Tremeac & Meunier (2009). In this paper the environmental impact of wind energy production is researched using an LCA. It is a comparison between two systems. They find critical factors to be wind availability, quality of the turbines, transportation emissions, and recycling after decommission.

The paper by Geyer et al. (2013) focused on PV versus biofuel production. I included three more papers on biofuels. Souza et al. (2012) researched a new joint way of producing palm oil and sugarcane ethanol was compared with a traditional sugarcane ethanol production in terms of energy balance and land use. Joint production proved to score better on energy production as well as environmental factors. The second paper on biofuels is Wang et al. (2014). This study compares the economic and ecological performance of biogas systems in China. Large-scale biogas systems are more sustainable than the other renewables in the comparison, but less so than small-scale biogas systems. The last paper on biofuels focuses not on crops for direct conversion into energy, but on a biological residue as an energy source (Yang & Chen, 2014). Crop residue gasification is a promising technology to produce sustainable energy because of its high energy efficiency. The study concludes that it has potential to reduce global warming impact. Its highest impacts are during operation and construction stages due to the consumption of the residue, electricity, and steel. The potential has overall been exaggerated.

Finally, a paper that could also be classified as methodological is Steinmann et al. (2014). They argue that the difference between uncertainty and variability is that uncertainty is unknown by the researcher, and that variability is known but not a constant. The authors explore weaknesses in applying these concepts in LCA. Using a case study on carbon footprints of coal-fueled power generation, and their model for separation of uncertainty and variability, they showed that it was mostly variability that caused the ranges in results.

OTHER TYPES OF LCA

Energy and waste proved to be the two largest topics, but of course an LCA can be performed on any product. I have chosen five other papers to represent different fields. It must be noted that these were much further down the list of LCAs in terms of citations, nevertheless it is good to include some other topics as well for diversity.

Eckelman et al. (2012) look at the environmental implications of a new medical instrument. The authors conclude that there is a growing awareness of the effect new healthcare technologies have on our environment, and therefore on public health. A laryngeal mask

airway is a new medical tool that keeps a patient's airways open. This study performs a comparative LCA on two versions of this tool. The two options had different scores in multiple categories such as waste management, washing, and packaging.

Construction is one of the major contributors to environmental burdens. A paper that could also be under energy efficiency LCA is by Fay et al. (2000) who perform an LCA on an Australian building to provide new information on making energy efficient buildings. Their conclusion is that, over a lifetime, insulation only offers a small reduction in energy of a building's life cycle, and that other options, such as general energy efficiency during construction, might offer better solutions.

Peters et al. (2010) research red meat production in Australia. They compare three different methods of production using LCA. This topic diverts completely from energy or waste,

An overlapping topic with energy is a paper written by Stasinopoulos et al. (2012). This paper is not a full life cycle assessment, but seeks to take steps towards one by compiling the life cycle inventory. The case they want to address is car body-in-whites in Australia made from either steel or aluminum, in terms of energy use. They conclude that the life cycle inventory has trouble acknowledging the benefits of aluminum because of temporal issues. Additionally, they conclude that the changes in material will, on a macro scale, not provide adequate reduction in energy consumption to achieve a sustainable impact. The last paper I looked at in this category was by Zackrisson et al. (2010). This paper is not an LCA in itself, but sets one up. It explores critical issues determining whether an LCA is possible. They find different difficulties and points of importance with conducting an LCA on this case.

After this overview of the researched cases, we have an idea what LCA's general characteristics are, and which cases are going to be used for analysis. In the next chapter I will discuss the weaknesses of LCA found in the literature. Ideally, an LCA paper includes many factors for quality management. ISO standards dictate that at least time, geography, technology, precision, completeness, representativeness, consistency, reproducibility, sources, and uncertainty must be discussed at a bare minimum (Ardente et al., 2005). However, as I found out, none of the papers I looked at discuss all of these issues. Sometimes they talk about some of them, but they do not include a clear list.

3.3 WHICH FACTORS INFLUENCE THE RELIABILITY AND USE ACCORDING TO LITERATURE?

Here I will answer sub-question two. The weaknesses found in the research are also based on what the papers presented and therefore I have only looked at the ones the researchers recognize themselves. It is very possible that the authors of the literature had flaws in their research that they were not aware of or did not present. By looking at a multitude of papers, I still found enough flaws. However, the larger works on LCA as well as the specific papers and their comparison have still shown to be a rich source of identified weaknesses in the methodology. The weaknesses have been identified for each paper individually, and then aggregated into larger weakness categories using an iterative and deductive process. Each heading presents an identified weakness category and its discussion, starting with the most important weakness based on number of occurrences. Because LCA issues are complex, there will be some overlap between categories. I have summarized these findings in a table below (Table 1).

Identified weakness category (times mentioned)	Sources
Uncertainty and assumptions (15/37)	Ardente et al. (2005).
·····	Baitz et al. (2012)
	Eckelman et al. (2012)
	Espinosa et al. (2012)
	Fay et al. (2000)
	Geisler et al. (2005)
	Gluch & Baumann (2004)
	Granovskii et al. (2007)
	Huijbregts et al. (2001)
	Manfredi & Christensen (2009)
	Pacca et al. (2007)
	Peng et al. (2013)
	Raugei et al. (2007)
	Steinman et al. (2014)
	Zackrisson et al. (2010)
Temporal and geographical issues (13/37)	Bogner et al. (2008)
	Christensen et al. (2007)
	Fay et al. (2000)
	Geisler et al. (2005)
	Geyer et al. (2013)
	Jørgensen et al. (2008)
	Pizzol et al. (2014)
	Reap et al. (2008)
	Schreiber et al. (2012)
	Souza et al. (2012)
	Stasinopoulos et al. (2012)
	Yang & Chen (2014)
	Zackrisson et al. (2010)

Data unavailability (10/37)	Ardente et al. (2005)		
	Baitz et al. (2012)		
	Geisler et al. (2005)		
	Gluch & Baumann (2004)		
	Huijbregts et al. (2001)		
	Parisi et al. (2014)		
	Peters et al. (2010)		
	Reap et al. (2007)		
	Yang & Chen (2014)		
	Zackrisson et al. (2010)		
Mixed data and comparability (7/37)	Baitz et al. (2012)		
	Bogner et al. (2008)		
	Christensen et al. (2007)		
	Peng et al. (2013)		
	Schreiber et al. (2012)		
	Wang et al. (2014)		
	Yang & Chen, (2005)		
Market effects (4/37)	Baitz et al. (2012)		
	Fay et al. (2000)		
	Granovskii et al. (2006)		
	Peng et al. (2013)		
Communication constraints (4/37)	Baitz et al. (2012)		
	Gluch & Baumann (2004)		
	Klinglmair et al. (2013)		
	Reap et al. (2008)		
Cutoff issues (3/37)	Eckelman et al. (2012)		
	Reap et al. (2008)		
	Yang & Chen (2014)		
Allocation (3/37)	Geisler et al. (2005)		
	Parisi et al. (2014)		
	Reap et al. (2008)		

Table 1. Factors influencing the reliability and use of LCA identified in the literature.

From this chapter it became clear that LCA is suffering from a lot of issues. Additionally, we can assume that many reports are not talking about all issues they encountered, as some lacked chapters on limitations and uncertainties. Therefore, the relatively large pool of literature cases compared to the interview cases balances things out between the two. In the interviews the participants provided me with very specific on topics information. I will proceed with going further in depth about the weaknesses presented above.

UNCERTAINTY AND ASSUMPTIONS

When talking about weaknesses in LCA I found that writers often talk about tradeoffs (Baitz et al, 2012). These tradeoffs are decisions between effective time and resource management versus completeness. Oftentimes an LCA is done for a company that has set aside these resources and time for the researchers to conduct the study. Academics and other institutions who are working on improving the LCA method are often pressured under resource constraints. One could say a perfect LCA – if such a thing exists – takes an infinite amount of time because data can always be more precise. This is an exaggeration, but uncertainty comes from the details in the data and process. In the paper by Geisler et al. (2005) the authors mention that their calculation of the flows of materials were likely imprecise because of this tradeoff. This is then an example of a paper where the authors made the decision to decrease the accuracy and thereby increase the uncertainty of their research willingly, so that it could still lead to results within their time and resource framework. Espinosa et al. (2012) admit that although their research adds value, a detailed assessment cannot be done at this stage as it would require more time and resources. It is not uncommon for an LCA to have these uncertainties. It is, however, not very common that the authors put clear indications in their studies about how these choices and consequential uncertainties reflect the research quality.

Of course researchers do not have an infinite amount of time so they must work with what they do have: choices and assumptions. However, the more assumptions a research contains, the vaguer and more distant from reality it becomes (Baitz et al., 2012; Gluch & Baumann, 2004). Peng et al. (2013), too, state that for comparison to their own research, previous studies just contained too many assumptions and uncertainties. Again, it is not always stated which assumptions were made and, after having read many papers on LCA, readers have to become suspicious of the ones that do not mention any at all (Steinman et al., 2014). Some that do give some attention to these factors are for instance Manfredi & Christensen (2009) who wrote about landfill depth estimations and increasing uncertainty. Pacca et al. (2007) mention that their estimations are based on prototype data and therefore contain uncertainties about the actual impacts. Raugei et al (2007) and Zackrisson et al. (2010) present a rare detailed account of their assumptions. Two interesting cases were Fay et al. (2000) and Huijbregts et al. (2001) who wrote that because of their assumptions, which were based on prototype batches, the findings of the study might not accord with the actual design predictions or the performance of the product. This statement alone greatly increases uncertainty, as with LCA one cannot always directly see the effects and we will perhaps never know if the results of the study were right or wrong. Eckelman et al. (2012) use different parameters to calculate the range within their uncertainty in product reuse rates, for which they use different recycling rate assumptions. This is a technique that works because of the wider range of conclusions that can later be looked at. But it has the added problems that it becomes messy when it has to be done for more than one parameter, and that it is not conclusive in itself and requires more research based on local conditions. Granovskii et al. (2007) say that the challenge is to maintain the main characteristics and functions of a product or system while making choices and assumptions. However, as

shown above, LCA research lacks a single technique for doing this. A rather large portion of studies do not mention uncertainty at all, some mention it and do not further calculate results and only a few actually do an uncertainty or sensitivity analysis.

Uncertainty is something that is affected by all other categories below as well, it is the main pillar of critique found in many papers. LCA standards do not offer a simple guideline to deal with the uncertainties, as they vary widely (Ardente et al., 2005). The term itself implies flaws in accuracy which, as we have seen in the previous chapter, is such an important part of why LCA is a strong methodology. Different assumptions do not always make for comparable results. From the researched papers it became clear that assumptions are a large contributor to increased uncertainty within a study. When authors are not clear about these, the readers cannot fully value and interpret the results they read. This can lead to wrong interpretations and therefore a misplaced trust in the study.

TEMPORAL AND GEOGRAPHICAL ISSUES

Reap et al. (2008) discuss the effects of temporal issues and changes, and how these influence results. They, as well as others, argue that the bigger this temporal scale is, the more uncertainty is introduced into the study (Christensen et al., 2007; Yang & Chen, 2014). The fact that temporal choices have to be made in LCA is unfortunate as LCA so heavily relies on the objectivity and accuracy of the research. Environmental impacts have effects over longer periods of time, where for example groundwater is slowly being intoxicated by a landfill over the course of decades. In this example, when we assume there is no other sufficiently comparable case to measure the rate of intoxication over time, the data needs to be approximated. This temporal issue leads to an increased abstraction in the data (Pizzol et al., 2014). Additionally, it is not always clear how to categorize these impacts (Jørgensen et al., 2008). The use of this data poses questions that in some cases cannot be answered. Should a research include impacts over fifty years, or a hundred years, or perhaps even more? This temporal cutoff is usually made in the start of a research phase based on what seems a reasonable time span by the researcher. It is not unusual to choose to look at several temporal scales. This choice can be challenging because of smaller uncertainties adding up over time (Bogner et al., 2008), and the effects of macro-scale effects over very long time horizons. The latter is often unknown, and therefore cut off in LCA research (Schreiber et al., 2012). Stasinopoulos et al. (2012) as well as Yang & Chen (2014) conclude that in many LCAs, temporal data is missing. The researchers only look at the direct effects, thereby nullifying temporality. This can be either done on purpose, for simplification, or in worst case without giving it proper consideration. The latter is an example of a flaw in an LCA that should not have been overlooked, directly influencing the quality. A particular problem mentioned by Geisler et al. (2005) is that they found their data has variations in parameter values over time. Measurements from different periods in time did not complement each other flawlessly. What causes these changes is not always clear or generalizable, as this differs per product category and perhaps

per single case. This shows the frailty of measuring snapshots in time of a product, and calls for repeated research into same category products, and their changes over time.

Geisler et al. (2005) also showed that not only in time, but also in space changes in data outcomes occurred. Reap et al. (2008) explain clearly that the reliance on global aggregated data sets is not always an accurate description of the single case under study. These global data, and even regionally aggregated data, are averages. Sometimes, research calls for the use of sitespecific data as local conditions may differ greatly. Especially supply chain research, where many data sources are compiled to score a single product, calls for greater care in using globally or regionally averaged data sets. However, this increased effort demands time and resources a researcher might not have. Studies that mentioned geographical constraints are for instance Zackrisson et al. (2010) and Schreiber et al. (2012), who said that their results may not apply to other climates and sites because the materials used react differently there. Christensen et al. (2007) offer a disclaimer that all emissions are ascribed the same environmental impact regardless of local conditions, and that data should be interpreted with care. Additionally Fay et al. (2000) warned about the local dependence of their research topic, waste treatment. Stasinopoulos et al. (2012) posed the interesting case that research that uses temporal points for simplification reasons limits the ability of a research to account for spatial effects, because these are interconnected variables. An LCA researcher eventually has to make choices regarding both temporal and geographical limitations. Either the temporal effects are unknown, or they are deliberately ignored. This is fine if it results in only minor changes in the outcomes of the research, but should be used with caution as the potential long-term impacts can be high. I have found that temporal factors are often included in research, as this choice is one that is made from the start when determining the scope. Geographical issues are mentioned less frequently, and if they are it is often a disclaimer mentioning the research should not be extended to other geographical regions. The weakness and potential impact of using averaged data sets is rarely discussed.

Finally, geographical issues closely relate to land use issues, which is why I chose to place them under the same heading. This topic turned out to be not as controversial as others, having only two mentions of it in the literature. Geyer et al. (2013) found that in their research on PV versus biogas use, land use changes lead to widely differing impacts in GHG emissions. Souza et al. (2012) found the same, where there were significant changes in results because of different land use scenarios. Land use issues arise when a product turns out to have the least impact on the environment, but requires significantly more land. Firstly, this land must be available, and often it is not. Secondly, this land must be suitable and similar to the initially researched land, because impacts might differ on different places.

DATA UNAVAILABILITY

An LCA requires precise data because it needs to measure environmental impacts as accurately as possible. ISO standards provide these data sets for a wide range of substances. Not all impacts of substances are known. This counts especially for those impacts over longer periods of time, as we have seen in the previous section on temporal issues. Geisler et al. (2005) for instance said that the knowledge they had of the properties of substances and their effects on the environment was imprecise. Other papers that mentioned a lack of sufficient quality data were Gluch & Baumann (2004), Peters et al. (2010), and Yang & Chen (2014). A major problem in this category often lies with knowing which substances are used, both in the product and during production. When looking at a supply chain of multiple producers, challenges lie in finding out which step uses which substances exactly. When a researcher are hired by a specific company to map the environmental impact of a product, companies in their supply chain might not allow them to have access to all information, or will provide lower quality data sets themselves. Ardente et al. (2005) as well as Huijbregts et al. (2001) suffered from this problem, as they lacked exact and precise data for all sites, resulting in a multitude of uncertainty sources. Huijbregts et al. (2001) additionally mentioned that a "major problem affecting the application of LCA-based tools concerns the data bout resource use and emissions, there is no actual monitoring" (p. 2). Others have found that although there is actual monitoring, the data was not available to them. Zackrisson et al. (2010) mentioned that there was a lack of cooperation with the manufacturer to provide data on battery manufacturing: while the data was available, they did not have access to it. Additionally, it can be unclear what happens to the product at the final stages, after the use phase. Parisi et al. (2014) had to settle for a cradle to gate research, as they lacked end of life data. Researchers should be transparent about these gaps in unknown data in their research. Not many researched papers dealt with unknowable data, so it seems to be a somewhat rare occurrence.

An additional problem encountered in data acquisition is that some of it is available from primary sources and some is not, and that because of this the sources inevitably differ. This leads to a seemingly random pattern in data acquisition choices where data from different sources is aggregated into the same analysis. Baitz et al. (2012) additionally warn for unidentified, fuzzy and outdated sources. This is confirmed by Reap et al. (2007) who say that generally, LCAs are prone to weaknesses in data acquisition steps. With these traps hidden in the details of an LCA, researchers must be very careful when it comes to their final conclusions. Ideally, every uncertainty in data is measured and mentioned in the discussion. However, because of the previously mentioned time and resource constraints, one can ask the question: how many tradeoffs have been made in favor of completeness? And if there have been made major tradeoffs, how many of these have influenced final decision making significantly?

MIXED DATA AND COMPARABILITY

Constraints put pressure on the researcher, which results in having to make choices. Earlier I discussed the cases of data unavailability and data assumptions. A third problem with acquiring reliable data is the pressure the researcher has to deal with, and the ease of use of random and mixed data (Baitz et al., 2012). When relatively easy to collect, but random, it becomes a patchwork process. The quality of data can greatly differ. This makes comparing your data a challenge, as it becomes difficult to distinguish between what are real problems with the research object, and problems with technical differences in data. Yang & Chen (2005) illustrate this problem by mentioning that for the different products under study have different production processes. This data had to be gathered from different producers, resulting in a myriad of data acquisition methods. Bogner et al. (2008) too had a similar problem, as data stemmed from different countries, which all had an impact on the preciseness and quality of the data. However, the constraints researchers have to deal with more often than not require them to use imperfect, and randomly patched data. Yang & Chen (2014) had this problem included in the uncertainty analysis, in which they were the only ones.

Not only does this issue affect internal consistency, it is of increased magnitude when comparing. Schreiber et al. (2012) plea for a more streamlined process of data acquisition and categories in CCS technologies, so that finally products and processes can be compared without having to address all the data flaws. Wang et al. (2014) too mention that other studies used different allocation methods for allocation of their data, stemming from different reasoning based on the data sources. This is closely related to the issue of allocation because of market effects described later. Mismatches in data types also happened in the research of Christensen et al. (2007), as well as Peng et al. (2013), where there was mention of a significant variance in types of manufacturing. The question that stands is, how reliable is the data in the resources that do not specifically mention patchwork sources. Some studies got access to the time and resources to acquire high quality data, while others might not have been so lucky. This stresses the importance of looking at the data sources and the internal consistency of quality, and external comparability.

MARKET EFFECTS

Cost effectiveness and market effects are optional parts of an LCA, but have increased significance in the field. Cost, like sustainability, is a factor a company has to consider when making a choice about their products. Often, costs are more important than sustainability. Market effects are closely related to costs, as the market predicts the price of different goods and services. Considering costs in an analysis is not an easy task, as the market shows fluctuations and new technologies present themselves as time passes. Granovskii et al. (2006) include a cost effectiveness analysis on their hydrogen fuel cells, and they find that it is rather challenging to predict the value of their product on the market as the prices and ease of production of other technologies fluctuate. Fay et al. (2000) include a payback time, to see whether investment in the technology researched would pay off, which is subject to the same fluctuations.

Peng et al. (2013) researched an interesting case which is effectively an allocation problem caused by market effects. When an LCA compares the impact of two products, perhaps one already on the market and a new design, market effects start to play a role. Peng et al. (2013) present the issue of energy mix, which is a country-specific issue. Different countries use multiple technologies to produce energy, which all have differing impacts on a range of impact categories. Firstly, it is not always exactly clear what the energy mix of a country is, and which specific technologies are used. Are coal plants an old model, or the newest, most efficient models? Energy is also often imported from other countries, with their own energy mix. As the prices of energy fluctuate, so do the technologies used to produce energy. The energy used is just part of a production process that is dictated by market effects, and already poses so many questions and forces assumptions. If a new technology is used, and it uses less energy, one can also ask which energy production it replaces. Baitz et al. (2012) confirm this problem, and state that many LCAs rely on the predictions of market effects. This category shows some resemblance to a social aspect of temporal and geographical issues, as market effects differ per country and per region in time.

COMMUNICATION CONSTRAINTS

When communicating an LCA, many things can go wrong. The personal attention span of the audience can be overstretched, or complex results can be simplified and generalized to such an extent that the conclusions are useless. Additionally, the personal views of the people to whom the LCA is communicated play a big role in the final effectiveness. Gluch & Baumann (2004) raised the issue of the decision maker's personal view of reality, which played a large role in the effectiveness of LCA. This is of particular interest to this research because in the interviews we will take a closer look at expert experience and after-the-research effectiveness. The authors raised the issue of communication constraints. Baitz et al. (2012) mention there is both synergy and tension between scientific development and the application of LCA. However, they continue by saying that the combination of research and application often leads to disappointment in LCA because the method's capabilities diminish when it is applied. The suggested objectivity is often reduced because of a wide range of subjective choices, as well as by having to be interpreted by a subjective end-user (Reap et al., 2008). Klinglmair et al. (2013) in their paper question the use of current LCA methodology in terms of the wider sustainability challenges, and argue that the use of LCA is widely debated. I have not been able to find this wide debate in the other literature sources for this research. I think the relative little mention of communication constraints lies with the issue that LCA papers and researches serve their own purpose, they do not have to look beyond the study and into the use phase. This is done behind closed doors, optionally in the presence of the researcher.

CUTOFF ISSUES

An LCA is done within its own product system. This means that the researcher chooses which effects to include as part of the system, and which to leave out. A practical example of this is looking at crops, where one would include the use of a tractor as part of the product system. But what about the production of the tractor, or the production of the raw materials to produce this tractor? ISO provides standards for this, and generally researchers choose clear boundaries for their system. Reap et al. (2008), however, show that the cutoff outputs in some cases have made noticeable differences. Eckelman et al. (2012) included labor, which is not usually included into an LCA, but which turned out to have significantly contributed to the conclusions of the paper. They asked the question whether labor should, for

this reason, not always be a part of an LCA. Yang & Chen (2014) argue that although they had a cutoff criterion determined for practical reasons, their understanding of many upstream and downstream processes was still limited. The variations they found in these processes however turned out to only make a minor difference in the conclusions. Further, cutoff criteria or issues were not mentioned so much in other papers.

ALLOCATION OF IMPACTS

Allocation is something every LCA researcher eventually has to deal with. Allocation is attributing a product's or process's impacts over different processes. Reap et al. (2008) describe it as "distributing environmental burdens of a multifunctional process". There are different methods to perform allocations, and ISO provides guidelines. Ultimately it is up to the researcher to decide which method fits the case best (Geisler et al., 2005). Allocation is a problem in LCA, as the choices made in this process greatly determine the outcome of the research. If the goal of a research is to find critical parts in a production process with the most polluting effects, allocating impacts to a specific part effectively determine the managerial decisions made based on this study. Geisler et al. (2005) had to make a significant choice for allocation, where the machinery used for making the product was also making other products. The energy used to keep these machines running was not completely distributed towards the products of their specific product. The question is, how much energy is distributed? A solid argumentation and reasoning are key in this somewhat subjective process. Parisi et al. (2014) mention a peculiar case where part of the production requires the use of vertical steel beams, but these also function to support the roof of the facility. Allocation was a particularly challenging issue here: how do you quantify the support of a roof needed to keep equipment and workers safe? The authors chose to allocate the full impact of the steel beam to their process, but make a footnote of this hard to solve issue. Allocation is a much discussed and well-known problem in LCA. However, as with many issues, it is challenging to for researchers to find the best solution to their specific case.

4. WHICH FACTORS INFLUENCE THE RELIABILITY AND USE OF LCA ACCORDING TO EXPERTS?

The literature review has provided me with data on academic findings about LCA and its flaws, but the interviews will provide me with the opinions of those with hands-on experience. I have been able to ask specific questions as well as find out the more practical flaws LCAs have, besides those in the research phase. I have contacted sixteen academics and experts from companies that use LCA, of which eleven responded, and of which nine were available to be interviewed. Factors that influenced the decision for nine participants were time and resources, but mostly availability of participants.

The interviews were analyzed using the same normative and iterative process as the literature. The interviewees all found LCA to be worth their time. This means that in their view

LCA is effective in what it does. However, all interviewees also said that improvement is possible on several points. All relevant points were listed, and then combined. Slowly, categories started to form, which resulted in the paragraphs in this chapter and can be seen in the table below (Table 2). I will tread in more detail in the separate headings below the table. It is clear that LCA is dealing with quite some issues in practice as all experts have identified several weaknesses. I will proceed to compare the results of the literature and interview findings in the next chapter.

Identified weakness category (times mentioned)	Participants
LCA is too complicated for end-users (7/9)	Adam Brundage
-	Anne Gaasbeek
	Diederik Schowanek
	Jeroen Guinée
	Krishna Manda
	Li Shen
	Niels Jonkers
Other factors make the decision, not LCA	Adam Brundage
(6/9)	Anne Gaasbeek
	Geanne van Arkel
	Krishna Manda
	Li Shen
	Niels Jonkers
Importance of comparing LCAs (5/9)	Adam Brundage
	Diederik Schowanek
	Flavie Lowres
	Geanne van Arkel
	Jeroen Guinée
Objectivity issues (5/9)	Adam Brundage
	Diederik Schowanek
	Geanne van Arkel
	Flavie Lowres
	Jeroen Guinée
Tradeoff between time and quality (3/9)	Adam Brundage
	Anne Gaasbeek
	Diederik Schowanek
Gap between academic and applied LCA	Adam Brundage
(3/9)	Diederik Schowanek
	Li Shen
Gathering data is difficult (3/9)	Adam Brundage
	Anne Gaasbeek
	Diederik Schowanek

Uncertainty is critical (3/9)	Adam Brundage	
	Anne Gaasbeek	
	Jeroen Guinée	
Impact categories are imperfect (2/9)	Diederik Schowanek	
	Niels Jonkers	
There are a lot of bad quality LCAs out	Jeroen Guinée	
there (2/9)	Li Shen	

Table 2. Factors influencing the reliability and use of LCA identified in the interviews.

The categories in this chapter do not completely overlap with those in the literature review chapter, as the participants of the interviews presented different points. I have deliberately allowed them a lot of freedom in the interviews, and only intervened if they were moving into matter away from the topic of LCA. This has resulted in them providing their own input, rather than them having to rate a preset of factors. Any overlap between factors presented in the literature and the interviews is not because I specifically asked for it, but because the participants presented them, which increases the validity of the points. I will start with the most often mentioned points.

LCA IS TOO COMPLICATED FOR END-USERS

The complexity of LCA is something that all researchers could well grasp themselves, as they are experts on the field, often with hands-on experience. Six participants mentioned that the method is too complicated to understand for its end-users. This included both managementlevel employees and consumers. Jeroen Guinée mentioned that when comprehensiveness and detail is required, in difficult LCAs, the amount of information is just too much to understand for decision makers. This tradeoff between comprehensiveness and resources was underlined by Adam Brundage, who said that applied LCA is under a lot of time and resource pressure, and that managers do not care about the details regarding uncertainty and choices made within the research. Especially if one is trying to standardize methods within whole industries, it is near impossible to provide clear useable results. Niels Jonkers provided the example of an organic waste tool, which proved to be too complicated for users. A second example he provided was an outrage over the results of an LCA, which the users did not understand correctly, resulting in the wrong choice being made. This, he said, was an example of how social constructs, rather than objective research, still dictate decision making. Krishna Manda went as far as to say that it was near impossible to present an LCA and expect management to remember it, Adam Brundage as well as Li Shen mentioned that no top management would read a full report. Diederik Schowanek spent quite some time explaining how LCA was too complicated for end users. However, Anne Gaasbeek, Niels Jonkers, and Adam Brundage proposed solutions to these problems using tools. They all said that reports are much too static and do not engage the user. Anne Gaasbeek in an expert in this field. and said it is important to include the decision makers from the start, which Krishna Manda mentioned as well. Adam Brundage added to this that there was no time to explain any tradeoffs or uncertainties here:

people have questions and the expert needs to provide the answers. Tools can be designed using single scores such as the system Adam Brundage proposed, using an ABCD tool. I should mention here that Geanne van Arkel specifically said that communication was not really a big issue, because you can always put it in a single score method. Krishna Manda, who advocated the use of LCA mainly as an awareness tool, said to give the management a topic they know something about already, such as CO₂. Li Shen too said that management wants a single conclusive graph, although different departments might read more or less based on their interests. However, this is something Diederik Schowanek did not agree with, as single scores take away too much nuance. Krishna Manda, too, said that everything has to be communicated at some point, even the negative points and big uncertainties.

OTHER FACTORS MAKE THE DECISION, NOT LCA

The methodology of LCA is both to find out product impacts and to create awareness within a company. This can be challenging, and five out of nine participants mentioned that LCA is not a decision maker. Often, Adam Brundage said, financial or performance indicators are valued much higher and are critical components, despite the results of an LCA. Niels Jonkers mentioned the use of shadow prices, where financial parameters still play a bigger role than actual environmental ones. Anne Gaasbeek too said that recent efforts to quantify natural capital were made to involve LCA in the decision-making process using something that management can understand. Krishna Manda said that it is important that an LCA finds the marketable attributes of a product. One should look at whether the LCA creates value in terms of risk, finance, or compliance. Geanne van Arkel, who was overall very positive about the use and impact of LCA, mentioned that if a product has the same price and quality, then a consumer will choose the most sustainable one. Lastly, Li Shen mentioned that management also needs to consider prices and process next to an LCA.

IMPORTANCE OF COMPARING LCAS

Jeroen Guinée proposed that all products should be mapped in an LCA-like manner. He mentioned European efforts to standardize this. Diederik Schowanek too talked about these efforts. He works with a group that wants to label all products in European supermarkets with environmental impact labels, much like there are mandatory labels for nutritional information now. This poses a lot of problems because there is little consensus on actual methodology. Adam Brundage, too, talked about this, mentioning the near impossibility of streamlining every participant in the Sustainable Apparel Coalition into using the same methodology and data. Geanne van Arkel proposed that the methodology of EPD was the solution to much of these problems, as it is a standardized form of LCA that allows for comparison between products. Flavie Lowres also talked at length about standardization efforts for LCA in the construction sector, and the clear need for comparable LCAs.

OBJECTIVITY ISSUES

Normalization in LCA is a way of weighing results against subjective values. I talked at length with Diederik Schowanek about normalization, but he did not identify it as a weak point of LCA. This point was in regards to normalizing results on the average European citizen, for communication of environmental impacts to these citizens. Two other experts specifically mentioned that normalization adds an unacceptable amount of subjectivity to an otherwise near-objective research: Jeroen Guinée and Adam Brundage. The former personally never uses normalization because of the added subjectivity. The latter said that if researchers normalize, for instance with regard to the preferences of higher management, it becomes a subjective approach. Tradeoffs between impact categories, he said, unfortunately often require this method. Li Shen, too, mentioned that weighting for single scores adds subjectivity. An additional problem with adding subjectivity is in the allocation phase, said Jeroen Guinée, where applied methods differ per case and choices are made by a subjective researcher. Additionally, Geanne van Arkel mentioned that LCA is a tool to be used for optimization, but is not a solid truth in itself as it contains subjective interpretations. This interpretation phase was also the main argument of Flavie Lowres, that the amount of different LCAs out there leads to a need for standardization, as there are too many subjective choices being made by researchers. Both Flavie Lowres and Geanne van Arkel gave me a very clear example of two competing companies with their own LCA experts showing opposite results.

UNCERTAINTY

Uncertainty has been discussed by all to some extent, but only three participants mentioned it explicitly as something that is really in the way of advancing the LCA methodology. Jeroen Guinée, Adam Brundage, and Anne Gaasbeek all mentioned this topic multiple times. This problem is somewhat connected to complication for end-users, as the uncertainty that is inherent to LCA is often impossible to communicate.

TRADEOFF BETWEEN TIME AND QUALITY

Adam Brundage told me that he advises not to spend too much time and effort on the research process. One knows beforehand that there will be tradeoffs and a lot of time can be won by making faster choices. Anne Gaasbeek would not agree with this, as she mentioned it is important to take these tradeoffs into account when calculating reliable results. Diederik Schowanek adds to this that LCA takes too long, and the results therefore often appear too late. R&D departments do not want to wait around for you to finish an LCA on their new product, they want to start making and improving right away. This is of course closely related to the communicability of the research.

GAP BETWEEN ACADEMIC AND APPLIED LCA

There is a large gap between academic and applied LCA. Diederik Schowanek argued that academics create new techniques and nuances all the time, but this only adds to confusion when you have to apply them. Adam Brundage as well as Li Shen identified this gap as well. She said that academic LCA could encompass an entire thesis, and could be interesting for the academic effort in itself without looking at impacts after the research. Management cares little about the science behind the results.

GATHERING DATA IS DIFFICULT

Something that was mentioned by only three interviewees was the issue of acquiring quality data. Anne Gaasbeek mentioned most specifically that gathering primary data was the largest problem in LCA. Adam Brundage mentioned it in reference to the Sustainable Apparel Coalition, where acquiring the larger datasets of all materials used was near impossible. Diederik Schowanek mentioned it on two occasions: gathering data is a time-consuming process, and by the time it is done it is mostly useless because R&D departments have already moved on. He later mentions that most of the work of an LCA is gathering data. Surprisingly, Niels Jonkers said that gathering data for an LCA at IVAM was not a problem at all, and was done fairly quickly and reliably.

THERE ARE A LOT OF BAD QUALITY LCAS OUT THERE

A connected problem to the importance of comparison LCAs that Li Shen mentioned, is that the quality of LCAs is not consistent. She said that there are a lot of bad LCAs out there. Jeroen Guinée confirmed this. Diederik Schowanek did not say it in these words, but he also said that a good LCA on a new product takes months to do correctly. Seeing that there are that claim to do it much faster, there must be bad quality ones out there.

IMPACT CATEGORIES ARE IMPERFECT

Niels Jonkers mentioned that there are difficulties with using impact categories because people know very little about them. How to value different impact categories when communicating results without having to resort to normalization? Sometimes it is also unclear to the researcher which impact categories to choose. Diederik Schowanek added to this that newer impact categories, like land use or water depletion, are yet to be defined and streamlined within the methodology.

5. WHAT ARE THE KEY DIFFERENCES BETWEEN THE FACTORS FOUND IN LITERATURE AND THOSE MENTIONED BY EXPERTS?

In this chapter I will discuss the final results of both analyses and provide a clearer overview of them. The results will be displayed in a graph, but I would recommend the reader to look at the graph solely as a summary, and look at the analysis more in-depth to get a clearer understanding of the issues presented here. Additionally, based on this aggregated analysis, I present recommendations for developers and users of the LCA methodology. This is a task list to address the current biggest issues with the LCA methodology found in this research. This list excludes some inevitable issues with LCA, as neither the literature nor the interviews provided useful recommendations to address these.

In the previous chapters I presented two tables representing the weaknesses identified in the literature and interviews (Table 1, Table 2). From here on I use the term *factors*, as the final result of this thesis should be a list of critical factors, which is part of the main research question. The results are ranked by the number of times they were mentioned in all papers or interviews. Six papers on the initial list were not included in these aggregated categories because they did not identify any weaknesses. This can have several reasons. They either did not report on any weaknesses in the paper; they did not have any weaknesses; or perhaps the scope of the paper was not to find out about weaknesses at all. I would like to note that the lack of a discussion in weaknesses is not specifically a negative aspect of the paper in itself. The papers that did not yield any results for this specific research are Tremeac & Meunier (2009), Tripanagnostopoulos et al. (2005), Rowley et al. (2009), Renou et al. (2008), Morris, J. (2005), and Kicherer et al. (2007). Of the interviews, all presented useful information more than once, and they were all included. They show different results, likely because the participants in the interviews use LCA in practice and therefore include their experience with application in their answers.

When comparing the total of eighteen categories from both the literature and interview data in detail, I noticed that four have a relatively complete overlap. This leads to a total of fourteen identified categories, which I renamed into fourteen more general factors (Table 3). The four aggregated factors' names were chosen based on the overlapping traits of the two categories. The new names for factors were chosen because they are a little more general, and compact. This provides a clearer picture when communicating the results, but of course lacks the nuance the categories or the in-depth analysis had. Whenever the reader is confused about a factor they can always trace it back to its source using the table (Table 3).

Literature category	Interview category	Factor
Uncertainty and assumptions	Uncertainty is critical	Uncertainty and assumptions
Temporal and geographical issues	-	Temporal and geographical issues
	Gathering data is difficult	Data availability
Mixed data and comparability	Importance of comparing	Comparability
Market effects		Market effects
Communication constraints	LCA is too complicated for end users	Communication issues
Cutoff issues		Cutoff issues
Allocation		Allocation
	Other factors make the decision, not LCA	Relative importance
	Tradeoff between time and quality	Time and quality tradeoff
	Gap between academic and applied LCA	Gap academic and applied
	Objectivity issues	Objectivity
	There are a lot of bad	Quality
	quality LCAs out there	
	Impact categories are	Impact category issues
	imperfect	

Table 3. Literature categories affecting the reliability and use of LCA; interview categories affecting the reliability and use of LCA and the factors.

In the research approach chapter I have explained the use of a formula for calculating the final results into a ranking system (Table 4). Notice that this ranking system only serves to provide a gross overview of the findings of this research, and no statistically relevant representation of reality. What it does make clear, is that some issues were mentioned much more often than others, and require the focused attention of users of LCA. I have added an additional visualization of the scores in Figure 2.

Factor	Literature %	Interview %	Score (max 100)	Rank
Communication issues	11	78	45	1
Comparability	19	56	38	2
Uncertainty and assumptions	41	33	37	3
Relative importance	0	67	34	4
Data availability	27	33	30	5
Objectivity	0	56	28	6
Temporal and geographical issues	35	0	18	7
Time and quality tradeoff	0	33	17	8
Gap academic and applied	0	33	17	8
Quality	0	22	11	9
Impact category issues	0	22	11	9
Market effects	11	0	6	10
Cutoff issues	8	0	4	11
Allocation	8	0	4	11

Table 4. Final list of fourteen factors influencing the effectiveness of LCA, their percentage of appearance in literature and interviews, and their aggregated scores.



Score

Figure 2. Visualization of scores for each factor, with a maximum of 100.

Now that there is a clear picture of each factor, and its gravity, I will discuss the outcomes with recommendations from the interviews. Firstly, I want to mention that every factor that made it onto this list is of significant importance, even the lowest ones. One of the lowest factors, allocation, was in fact mentioned a single time by one participant in the interviews, as part of a discussion on objectivity. In order to not double count this example I put it under objectivity as the participant did not further elaborate on the use of the word allocation. More of these connections between categories, and ironically allocation issues I had, will be discussed. There will also be recommendations for both researchers and end users of LCA. The recommendations are based on the findings of this research in both literature and interviews and are meant for improvement of the methodology.

The clear winner is 'communication issues'. These were mentioned in seven out of nine interviews, and in literature. Given that literature will rarely discuss this as they focus on the research phase, it is striking that expert interviews were able to compensate and push it to rank one by a rather large margin. This issue is one that has to be dealt with delicately, as it is essential for the effectiveness of an LCA to be communicated properly to its end users. The recommendations from this factor are largely based on tips and tricks the interview participants provided:

- Develop tools for communication
- Engage the end user from the start
- Keep conclusions short and elaborate later only when needed

Secondly, a strikingly important category in both literature and interviews is comparability. There has been an increased call for homogenization of the LCA methodology for comparison between studies. Many examples came from all these five experts, from the construction sector to the apparel industry. In literature too there have been examples of results that proved to be incomparable. From the interviews came the following recommendations:

- Homogenize the methodology
- Create databases for product categories

Thirdly, uncertainty and assumptions are a factor most discussed in literature, but this also came forth many times in the interviews. This is a broad factor with many implications, and its connections with others are undeniable, as it is often a result of another factor. For instance, more objectivity or market effects lead to an increasing number of assumptions, which can lead to more uncertainty in the research. However, the factor is important to single out because a researcher should attempt to fix this issue as well as possible, by reducing any uncertainty and making only solid assumptions.

- Reduce any uncertainty

- Make solid assumptions

In fourth place comes relative importance, pushed up by the interviews as it had no mention in the articles. This factor has its origin in the fact that LCA is not the only influence in decision making, and costs often are more important. The recommendation for this is:

- Use the LCA to create value for the end user

Data availability is high in the ranks too on fifth place. It is a rather straightforward category and another inevitable part of LCA. It is highly case specific and must be dealt with as well as possible. In the literature, this is something that would be discussed more easily, as opposed to for instance communication issues. Data collection is an important part of LCA. There are close ties to assumptions, as unavailable data will have to be dealt with using those. I was not able to find recommendations for improvement of the methodology on this part.

Objectivity constraints are, as mentioned above, closely linked to uncertainty and assumptions. However, objectivity as a general category is an important consideration for researchers and end users. They should ask themselves whether their specific LCA is really an objective piece of research, or whether indeed the uncertainties and assumptions have a profound impact on their results.

- Improve the methodology for assessing the level of objectivity of an LCA

In the literature cases, temporal and geographical issues showed to be of significance, being the second largest category there. They were not discussed in the interviews so much, but could be linked to the factor of imperfect impact categories. Category issues were only mentioned by two interview participants, where they described that new impact categories were less tested and uncertainties arose from that. Here, among others, the interview participants described land use issues. Temporal issues as described in the literature did not see a return in the interviews.

- Improve the methodology to deal with new impact categories
- Create databases for temporal and geographical differences

Time and quality tradeoffs are an important part of a researcher's considerations when performing an LCA. They were mentioned in the interviews as something of high importance. They did not make it into the highest ranks of the final list, because they were an individual category somewhat connected to cutoff issues. It was a subjective choice to split these two because of their differing nature. In this category, the researcher decides the goal, scope and system boundaries. This decision can be based partially on the time and resources available. This category did not yield any useful recommendations for improvement of the methodology. The interview participants recognized the gap between academic and applied LCA as an important factor; however, I have not included this in the literature analysis as a separate category. Baitz et al. (2012) do in fact mention this problem, as their paper is on the LCA methodology. However, it is not mentioned in papers that are actual LCAs, and therefore did not make the cut as a separate category, with only a single mention.

- Reduce the gap between academic and applied LCA

Quality is a problematic factor, as opinions differ on what a quality LCA is. Some academics have much higher standards and find certain assumptions unacceptable, while others do not care about these issues so much, as long as they do not influence the results too badly. There is a temporal aspect to this too: there was a clear disagreement between the interview participants on how much time an LCA should take. Quality is closely related to uncertainties and assumptions, as well as to objectivity. However, if researchers and users apparently do not agree on what a quality LCA is, there is work to be done to make the methodology more consistent. Lastly, this factor is perhaps one of the causes of the gap between academic and applied LCA, hinting to another connection between factors.

- Standardize the quality of LCA

Impact category issues were only mentioned in the interviews, and are mainly related to either unfinished, new, or unclear impact categories. However, as the methodology develops it is likely to assume these impact categories will be further expanded upon. The solution to this problem is therefore quite straightforward.

- Focus extra effort on solidly defining new impact categories

Market effects had some representation in the literature, with costs creating uncertainty on a temporal level. These effects can be related to temporal issues, as the costs of products fluctuate over time, but I chose a standalone category because of its wide representation in the literature. It was not mentioned, however, in the interviews. The recommendations for this I found to be closely related to those for the temporal and geographical issues, so I will not mention them here again.

Cutoff issues, as discussed previously, have been linked to time and quality, as a choice to deal with resource constraints. However, these issues are usually a necessary part of an LCA as cutoffs of a system boundary must be made, otherwise a research becomes infinitely big. For researchers, it is important to ask themselves where results still matter. Does my exclusion of a certain process from my research no longer significantly impact the results? Lastly, I have used allocation issues earlier as an example of a lower scoring factor that is still of importance to consider, so I will not discuss it again here. It is another inevitable category in LCA, a choice

that has to be made. Neither the literature or interviews provided me with insight in possible recommendations to improve this. I will now present the conclusions in an orderly fashion, after which I will provide recommendations and a reflection.

6. CONCLUSIONS

The research question was: What are the main factors the LCA methodology faces that *influence its effectiveness?* To find the answer to this question I have analyzed several academic papers and books, and conducted in-depth interviews with experts focused on practical as well as methodological issues. The literature analysis provided an example of issues that researchers mention in their papers, with a focus on issues during the research phase. Thehe interviews provided much more in depth results. Uncertainties and assumptions are an inherent part of LCA, and to communicate the results and these flaws to the end user proves to be the most challenging. From the interviews it became clear that different tools are being developed for this, as well as big projects such as in the construction or apparel world, where sustainability through LCA is gaining ground as part of the business model. Part of the goal of these larger projects is being able to compare LCAs, which also has shown to be a significant issue. There are different LCA, and LCA-like, methodologies out there. Different companies and countries have different standards and therefore the methodologies are not streamlined. For consumers this means confusion in terms of who to believe, and which products to buy. One main factor was also the relative importance of LCA, and therefore sustainability, in organizational decision making, which was often cited as third after cost and quality of the product. Efforts to include costs in LCA have been made, but are not an integral part of the LCA methodology generally. Another major issue is data availability, where quality data is often scarce or has to be approximated. The assumptions made here show similarities to the more general assumptions category. However, efforts to standardize data in for example the construction or apparel world have lightened this burden of uncertainty somewhat, and are an example of a solution to this problem. Objectivity too, was clearly an issue. Too many assumptions influence the objective nature of the research. LCA is supposed to be a relatively objective look at the reality of a product. End users of LCA such as the management of a company are generally also not interested in the exact level of subjectivity involved in the research, and, by making the final decision also based on other factors, add even more subjectivity themselves. Another factor of influence is temporal and geographical data issues, where across the globe and depending on the time scale results may differ. More issues with lower scores on the list are time and quality tradeoffs, the gap between academic and applied LCA, quality, impact category issues, market effects, cutoff issues, and allocation. Some of the discussed issues also yielded recommendations to focus on for improvement of the factors, and some did not.

To come full circle, it becomes clear that LCA research still has a lot of issues. Some of these issues can be worked on and for some there seems to be no definite answer. But from the interviews it became clear that, during the communication of results, companies are not very interested in many of the weaknesses, they just want results. Additionally, LCA is not just a tool for direct improvement, but also for the creation of awareness of sustainability issues. By using LCA, a company is already dividing part of its attention to these issues. This means that these weaknesses can be seen in perspective to the inherent positive impact of awareness. It is important to realize when doing an LCA which of these issues apply to your LCA. What is the amount of risk that this factor includes into my LCA? Does it influence the credibility of the results significantly? An already widely recommended approach for this is to do a sensitivity analysis over the data, but some issues go beyond data. Clearly, there is not always time to research all weaknesses, but it is important that one is at least clear about the limitations it introduces.

6.1 RECOMMENDATIONS

Recommendations for further study on this topic would be a continuation of this paper, but looking more in depth into solutions to the problems found. Additional research could make an attempt to make the results shown in this study statistically relevant: I did not do this because of time and resources. During this research, I found that issues greatly differ per product or service. Although there are some general issues in every field, which are highly ranked in my results, trying to make results statistically relevant was not useful for this particular research setup. Had I known the great difference between fields beforehand, I would perhaps have focused more on a single field. Lastly, perhaps one could also contact the authors of the literature analyzed, and ask them about issues that were not mentioned in the paper.

The final list of recommendations, and the answer to the final research question *How can the LCA methodology be further improved*? is as follows:

- Develop tools for communication
- Engage the end user from the start
- Keep LCA short and elaborate later only when needed
- Homogenize the methodology
- Create databases for product categories
- Reduce any uncertainty
- Make solid assumptions
- Use the LCA to create value for the end user
- Improve the methodology for assessing the level of objectivity of an LCA
- Improve the methodology to deal with new impact categories
- Create databases for temporal and geographical differences
- Reduce the gap between academic and applied LCA
- Standardize the quality of LCA
- Focus extra effort on solidly defining new impact categories

The largest difference between the literature and interviews could perhaps be the nature of either one. In academic papers, LCAs are often presented very solidly without many issues. However when one asks a researcher about the gaps and weaknesses of LCA problems start to

surface more easily. Because I could ask interviewees direct questions, and because literature does not always answer all questions automatically, it was important to have more cases of literature than interviews. Although I have presented a table with all the resulting factors, the linkages described here are also present. This shows that the issues LCA has cannot be divided into parts so easily. There are always interrelations and connections. The recommendations this research provides are therefore not to be tackled individually per se. If one were to work with this list on improving the LCA methodology, they will almost surely experience the interconnectedness of the issues, as I have doing this research.

6.2 REFLECTION AND LIMITATIONS

There are some limitations of this research I should be clear about, to prevent misinterpretation of the results. The goal of this research was to find out the factors that influence the effectiveness of LCA. An issue with the literature analysis was that papers were not all discussed all aspects, as well as that some aspects that might have played a role were not considered by the authors. Additionally, the outcomes, and especially those of the interviews, are not statistically relevant. The calculations for the final table, which serves as a visualization of the issues found from these cases, was based on a too small pool of variables to work with statistical analysis. For this research, this means that it is important to read the interviews in Appendix 3 and understand what the experts are trying to communicate, rather than trying to theorize in a generalized way over their statements.

By searching Scopus for literature and filtering on citations and time, as well as looking at older course material from Utrecht University, I hoped to find quality LCAs in relevant fields. However, this still introduced a possible bias of a lack of papers that are not taken up into the Scopus database, or that have fewer citations. This could have an effect on the final results, as the researched papers have a focus on a few important fields of LCA such as solar energy, wind energy, and waste. Other product fields might experience other difficulties. Note that not all papers focused on these issues, and there are some from different fields still.

From the interviews it became clear that often the process of an LCA is not much a duality of research and implementation as I assumed. This means that there is less of a boundary between researcher and the research object, where the research is part of the communication. As an example, during the interviews it became clear that ideally, the maker of the product and the researcher have multiple points of communication during the research. This leads to understanding of the work of the researcher, and an increased effectiveness in the end results. It is rarely the case that a researcher independently does their research and then, in one final presentation or executive summary, attempts to communicate a complex research as LCA to the end users.

Some papers that were part of the analysis did not include a discussion of weaknesses. I am willing to presume that researchers have taken great care to limit these. However, this lack of transparency is little reassuring, and papers might still be subject to several weaknesses even though the author did not mention them. This became very evident in a course I took as part of the Master's program for which I am writing this thesis. One of the assignments was to analyze an LCA, and identify its weaknesses beyond those written in the paper itself. The final results were at times rather shocking, as many additional weaknesses were found. This leads me to the inevitable conclusion that at least some part of LCA research is not clear about its own limitations. To make sure this did not influence the result I have used a large pool of literature cases, and the interviews should help reduce the impact this issue as well.

For those who will draw conclusions from the numbers presented in Table 4, keep in mind that I have assigned every occurrence of an issue in literature or interviews a value of one. They have been added up in the final result. However, if one examines the interviews and literature closely, it becomes obvious that some issues are emphasized more than others. This means again that the results are not solid enough for a statistical analysis, because a lot of nuance is lost. I would urge the reader to read the interviews analysis, literature analysis and conclusions as they are presented. Ardente, F., G. Beccali, M. Cellura, V. Lo Brano (2005). Life cycle assessment of solar thermal collector: Sensitivity analysis, energy and environment balances. *Renewable Energy* 30.

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APPENDIX 1: INTERVIEW QUESTIONS

Question

Introduction. Is it okay if I record this interview for personal use?

Could you briefly introduce yourself and your role within [COMPANY] in regards to LCA?

What are the biggest issues or weaknesses you experienced with LCA?

Do you have examples of cases where LCA did not have the desired effect?

Does LCA contribute to the improvement of environmental issues?

How do you see the future of LCA?

Is there anything you still want to add to this interview?

Is there anything you would still like to know about me or this thesis?

Can I, and how should I use your name and company name in my thesis?

Would you like to receive a copy of this thesis?

Table 1. Interview questions (English).

Vraag

Introductie. Mag ik dit interview opnemen voor persoonlijk gebruik?

Zou uw uzelf kort kunnen inleiden, en uw rol binnen [BEDRIJF] en uw ervaring met LCA?

Wat zijn de grootste problemen of zwaktes va LCA in uw ervaring?

Heeft u voorbeelden va LCA waar het gewenste effect niet behaald is?

Voegt LCA iets toe aan het oplossen van milieuvraagstukken?

Hoe ziet u de toekomst va LCA?

Is er nog iets wat u wil toevoegen aan dit interview?

Is er nog iets wat u wil weten over mij of deze thesis?

Mag ik uw naam en bedrijfsnaam gebruiken in mijn thesis, en hoe?

Wilt u een kopie van mijn thesis ontvangen?

Table 2. Interview questions (Dutch).

APPENDIX 2: LITERATURE CASES

Ardente et al. (2005). Life cycle assessment of a solar thermal collector: sensitivity analysis, energy and environmental balances.

Baitz et al. (2012). LCA's theory and practice: like ebony and ivory living in perfect harmony? Bogner et al. (2008). Mitigation of global greenhouse gas emissions from waste: conclusions and strategies from the Intergovernement Panel on Climate Change (IPCC) Fourth Assessment Report. Working group III (Mitigation).

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Eckelman et al. (2012). Comparative life cycle assessment of disposable and reusable laryngeal mask airways.

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ADAM BRUNDAGE, ADIDAS

Adam Brundage is part of the innovation team within Adidas and plays a role in a team that looks at new techniques in products. This team has the task to look at social and environmental factors in products, where they look beyond compliance level technologies from a bottom up approach. This means that they will look at individual manufacturers and other actors in the supply chain. There is a special focus on energy and water consumption.

When Adam Brundage first came to Adidas, there was no LCA-based developed methodology to quantify sustainability within the company. The concept was not definable and therefore not approachable enough. He set up a methodology for defining sustainability for Adidas products, using GaBi software. He first designed models, then gathered the database for all the products used and finally performed an analysis. This approach was LCA-based, and because of that they had to find a way to make the outcomes useful without spending too much time and effort on the research process.

What proved to be a solution for this was to make a model instead of a report. Reports are static and provide only a snapshot of products. This cannot be implemented when a new product enters the line, or when old products are changed or removed. A model proved to be useful beyond the initial research phase. The model's parameters can be adjusted for maximum impact reduction or ranking options. In this way the company can keep measuring their impact over longer periods of time, and base consecutive decision making on updated data sets.

There are some smaller uncertainties concerning the categorization of impacts, as well as with generalizing a footprint for a single product. However, this tool is meant for management level decision making, and not for research on specific numbers. He also identified a gap between applied LCA and its academic variants. Applied LCA is often under much more time and resource pressure, and methods such as uncertainty statistics are rarely found relevant by management teams.

Concerning the impact categories, Adam Brundage told me that it was challenging to translate them into touchable subjects for communication to management. There is no time to investigate and explain a trade-off between one or the other. This would also require a subjective approach where the results are normalized to the preferences of higher management, e.g. do they choose to use more water to be less toxic? The European initiative, using Product Environmental Footprinting (PEF), is currently working on an ABCD based scoring system, that Adidas is playing a role is through their relationship with the Sustainable Apparel Coalition (SAC).

Another challenging aspect he found was explaining the results to others. People come with questions he has to answer without delving too deep back into the methodology and uncertainties. Additionally, LCA is not the decision maker. Often costs of production and performance indicators are the main drivers for decisions. Therefore, he argues, LCA is best

used to augment decision making, and create awareness within the company, and as a tool for communication to the customer.

As mentioned before, Adidas is part of SAC, where competing brands come together for attempt to create an overarching sustainability network. They want to streamline supply chain measurement tools and rules, but therefore have to acquire a great amount of materials data. So far, Adam Brundage said, the coalition has lead to some disappointment as the details in the inventory data are severely limited. There are just too many people and processes in a project of this scale. Additionally, some smaller brands do not have the capacity to deliver the data on time, or at all. However, he stresses the importance of the project as well because in the meantime, uninformed decisions are being made within many companies. There is a definite need for streamlined assessment tools.

In the future Adam Brundage would see LCA as a tool that requires more transparency to consumers. The need is there, but also still many complications. The fact that the EU is now meddling with tools as these and supporting companies to use them is helping somewhat. He hopes that in the future consumers will make choices based on life cycle data, in the same way that it is now standard to put contents of a product on the back.

ANNE GAASBEEK, PRÉ SUSTAINABILITY

Anne Gaasbeek told me that at Pré Sustainability they were the first to use LCAs, and develop a software tool for using these, SimaPro. Therefore they focus mainly on how to do LCAs and how to calculate the results in an accessible way. The tool also had to cater to different kinds of LCAs, from the broad ones to very specific ones. She specifically focuses on this usefulness of LCA. How do I make an LCA? How do I make it useful? How do I make it understandable?

If there is one thing that became very clear from our talk, it is that if you decouple LCA from the decision maker, it is too late. You have to start involving the decision makers from the start. It must be clear to a client that before you start your research, you do it together, with marketing and R&D present. It must be clear that there is only one way to get an LCA to be useful, and that is to do it together.

She added to this, that it is really noticeable when you involve all parties from the start. Immediately it becomes clear for everyone what the relevant issues are. This also helps determine the goal and scope of an LCA, as the clients basically provide these themselves by communicating their wishes. However, people must make time for this, and within companies getting people's time is not always that easy. Additionally, they must feel like they are spending this time in a useful way. There is always the question on how you get people to feel that they contributed to the process positively. If there is no feeling of engagement, the LCA will likely end up on the bottom of a big pile of papers influencing the final decision.

A new thing that she does to prevent this from happening is developing tools that companies can use themselves. Companies can upload their data into an LCA-based tool and make their own adjustments. This means that non-experts in the field of LCA can use it. This of course comes with some problems, such as that LCA is inherently a complex tool with a lot of tradeoffs, decisions, and uncertainties. It is of vital importance that from the start, the complexity of the process is clear to the users of these tools.

When they piloted this idea of tools, it did not work. There were too many parameters to keep in mind and the tool had to be simplified. Nowadays, the models are greatly simplified. The choice however is which things to adjust so that the model does not lose validity. This still requires some expert input oftentimes such as for allocating product and transport impacts. An example of the tool they deployed is SimaPro Share & Connect.

LCA, she mentioned, is always in development and for now it is the only way to really map environmental impacts in a quantifiable way. Yes, there are tools such as Cradle to Cradle that are easier and show a clearer picture, but the basis remains complicated. Additionally, Cradle to Cradle is more a vision than a tool, LCA does not have this vision and just attempts to quantify results. Cradle to Cradle is perhaps a strategy, but LCA is more useful for a strategy.

We also discussed social LCA, about which she said that there is a need for it. People demand to know where products come from and what their social impacts are. This however sometimes goes beyond your own organization, deep down the supply chain, and becomes a matter of accountability. A problem with this is how to quantify this need, which is doable for some parameters such as amount of days spent on vacation, but there are also showstoppers, such as child labor. From social LCA we briefly jumped on the case of Life Cycle Costing. She said that this method was up and coming, with a focus on the improvement of quantifying natural capital. We have to start looking at the costs and benefits of this capital.

One of the biggest problems LCA is dealing with is gathering data. Getting primary data is often difficult because of availability or transparency, and getting secondary data has reliability problems. Both of them increase uncertainty in an LCA. Of course, researchers have to do a tradeoff between resources and time, where they often choose for the simplest way of data collection. A challenge is to take into account these assumptions and uncertainties you make along the way.

Anne Gaasbeek provided me with an example of a project she was part of regarding the issues with assumptions and uncertainties. The research and development department of a company had some targets, of which one was that there should be less SO₂ in packaging. She went to talk with them about LCA from the start, as she mentioned before is the best way to approach the method. Together they developed a model that was as robust as possible, and they applied it in a workshop for the department. During this workshop, she mentioned all the assumptions made during the development of the tool. This both created activity and thereby awareness. LCA, she concluded, remains a tool. Without it we would have less insight.

DIEDERIK SCHOWANEK, PROCTER & GAMBLE

We started our interview with an introduction, where he talked about the nature of his work at Procter & Gamble. He works mainly on the more upstream methodology and concept development with regards to Life Cycle Thinking , and has less experience with LCA hands-on

calculation work. His role is to find out what to do with an LCA, and how to use it strategically and effectively (inside and outside the Company). He works with sustainability analysis tools such as LCA, Carbon Footprinting, and Product Environmental Footprinting. He also works closely with the European Detergent Industry (AISE) and the European Commission in a Product Environmental Footprint Pilot to explore an LCA-based standard for environmental information on products in supermarkets. With this group, he is trying to find environmental parameters to report that people will understand and be able to interpret usefully, like a label on electrical equipment.

After this introduction we discussed weaknesses of LCA, which he told me there are many of. Firstly he mentioned impact categories. Some are solidly defined, but others are newer and therefore do not have this solid definition, and are likely to undergo further developments. Examples of categories he said were ecotoxicity, land use, and water footprint. These categories suffer from uncertainties in actual impact calculations and or data availability. They are also difficult to use in a research and interpretation phase. Internally, within a company, they seem to function alright with appropriate caution. However externally, towards customers, these are more difficult to communicate.

A second weakness is the interpretation by non-experts such as management and consumers. He said that you often have to simplify results and use comparisons and analogies to effectively communicate the results. There is much research going on how to do this, such as a single score. He does not prefer this method, as it allows for very little improvement opportunities. It becomes a matter of yes or no, and much nuance is lost. Secondly one can use weighting and normalization, where he mentioned mid- and end-point normalization research by Gert Van Hoof. It is in general important to communicate several relevant impacts. He does this preferably by presenting the results to management in a spider web graph, where the product with the smallest total area shows the best results. During this communication phase it is easier of course to present to people that already know about environmental issues or LCA, and then you can present more details. To others it is important to show hotspots and fix these. This can be challenging if the hotspots are part of the background process, such as for instance with net energy use.

A third challenge is that there is little consensus between LCA users. Methodologies, choices and assumptions often differ somewhat , which results in incomparable outcomes. This problem especially occurs when comparing results in detail. ISO standards leave a lot of room for the methodologies to differ. He mentioned the European effort to communicate environmental impacts on supermarket products as an example of an effort to make results more standardized and comparable. They do this by creating standardized databases for product LCAs based on 14 indicators. Additionally, there is the example of carbon footprinting on products, which succeed partially but still showed a lot of variation in methodology.

The last weakness he mentioned was that an LCA often takes too long. It is a time consuming process and presents its results too late. When a company is developing a new product, they want to know the impact from the start. Often times the LCA has not been started yet at this phase, because there is no data available yet. Because of this LCA lags behind and misses the opportunity to have a meaningful impact. It is therefore hard to convince and R&D department to use LCA and to consider its potential usefulness. This problem can be prevented by being prepared, and work with a simplified LCA-like method instead.

An LCA, he said, can be done in a few days only when it is based on an older product which changed. This means that much of the previous work is already done, and only a few parameters have to be tweaked. A new LCA however takes months, and cannot be done quicker. Most of the work of an LCA is gathering the required data. When you work with ISO standards, it is also important to have a peer review session, which adds even more time to the process.

Other issues he mentioned more briefly were that LCA is not measuring impacts, but estimating them. In other words, you cannot validate your results in the real world. This is also because LCA is not linked to a defined space and time. Additionally, choice of functional unit and goal and scope often create confusion within working groups. Often, the performance of the alternatives you compare in an LCA is not fully identical. Here, the goal of an LCA to provide insight backfired into creating less insight and more division. He gave the example of a glass and plastic bottle comparison, where people do not see them as comparable products. Additionally, sometimes an LCA does not provide a clear winner when comparing products. LCA is very important because it implements life cycle thinking into a company or with consumers. The whole concept does contribute to the improvement of environmental issues because you have to measure and know the hotspots first before you act. It is an important manual to deal with problems in the future, instead of just moving environmental problems around. An LCA is voluntary, so that decreases its effectiveness somewhat compared to the impact of for instance emission laws. However, he presented an example of the AISE' Charter for Sustainable Cleaning, who focus on LCA for the whole detergent market, where producers collaborate in the same direction to improve their product. By regularly tracking the improvements achieved, it can be shown that the LCA approach leads to environmental improvements.

He foresees a bright future for LCA. Where in the nineties people had never heard of the method, CEOs now likely have. There has been significant process in both the acceptance of LCA, as well as on the technical side. A danger that still lurks is that there are many different methodologies within LCA, that are great from an academic point of view, but creates more confusion for applied LCA.

FLAVIE LOWRES, BRE GROUP

We started the interview with a little introduction in the history of BRE, and how Flavie Lowres is involved with LCA. BRE Group was originally a public company, that became privatized in 1997. They developed industry standards by testing, leading innovation, and third party certification for the construction industry. They developed BREAM, the BRE environmental assessment methodology, which measures the environmental performance of buildings in terms of energy, acoustics, materials, lighting, and more. At BRE research consultancy, they develop testing methods and standards to improve the industry, which can support BREAM. This is where LCA comes in, because they whole assessment methodology is based on LCA. They have been updating databases since LCA started around 1990.

She said that although LCA is about twenty years old now, it is still young in development. Many industries have only recently started to adopt LCA. Construction is probably the farthest ahead, because they have the largest impact on environmental indicators. Both the acquisition of resources, as well as the use of buildings uses a lot of energy and materials. This wide range of materials and results that have to be measured in an LCA leads to confusion in the interpretation phase of the results. When you are measuring carbon, water, ecotoxicity, and waste, how do you know your product has improved? Because ultimately, the goal of LCA is to measure impact and reduce it. She said that this remains an issue within LCA, but they use the Green Guide of Specification, in which it is specified how to use the functional unit.

She mentioned that the subjectivity of the interpreter also plays a role in the effectiveness of LCA. She gave me a classic example of disposable versus reusable diapers, where two LCA researches had opposite results. I guess the problem here is, she said, that the methodology is open. Although every party uses the same ISO standards, results are open to interpretation. In construction, the European Commission developed an LCA standard. The whole process is harmonized, but even still the outputs are huge lists of numbers and although the standards were a good start, they now expanded to whole building assessments. This means that instead of measuring the impact per wall or floor, they measure it per building. It is still hard to compare results, which is better and which not. Now they are working on expanding their database by rewarding companies to do an LCA, but are not yet ready to interpret the results.

The European Commission really played a huge role in the advancement of LCA. Sustainability is becoming bigger, LCA is becoming bigger, but the method needs improvement. A final problem with LCA she mentioned just before we finished the interview is that there are different software packages out there who use different databases.

GEANNE VAN ARKEL, INTERFACE

As head of the sustainability department at Interface, she works with the company to optimize their sustainability performance. Additionally, she looks beyond the company's sphere of influence. LCA is really a method to define objectively which product is smarter to use in terms of social or environmental sustainability. The choice is often rather difficult, but LCA helps to show to true impact of products.

Geanne van Arkel very enthusiastically told me about her work with a standardized variant of LCA, the Environmental Product Declaration (EPD). This is a standardized form of LCA using ISO norms, which makes comparison between products possible. This is important because the assumptions between companies differ. She provided the example of towels, where an electric dryer company will tell the client people use three times as many paper towels

compared to one use of their product, while at the same time the paper towel company will tell the exact opposite. If one wants to do an LCA internally that is fine, but when you want to use it to compete, the EPD provides answers. The European Union is currently working on implementing this standardized form per sector.

However, even a standardized form of LCA like EPD does not guarantee comparability. There can still be differences in functional unit, social impacts, or context. This social aspect, she told me, is something UNEP and Pré are currently working on. However, this methodology lacks objectivity as well as a clear value judgment. It is unclear how to interpret the results of such an LCA. However LCA in general is a tool, not a solid truth. You have to include these other points. Look at the whole product, and use an LCA as part of the story.

A weakness of general LCA, which already became somewhat clear, is that it is not standardized. The consumer or buyer cannot compare two products. EPD is an answer for this. On a consumer level, one can think of labeling comparable to nutritional information. Use impact categories and a single score to summarize.

An example she gave of an LCA that worked well for the company was one that calculated whether the reuse of lost fishing nets was environmentally beneficial for the company. The same fibers, nylon, are used in carpeting. The LCA turned up with positive results, and now they are using fishing nets from Scandinavia and the Philippines. Additionally, the social dimension she talked about earlier came back here, as fishermen have now more sustainable livelihoods, as well as extra income for more boats or education.

A disadvantage of LCA at the moment is that many people do not realize the impact of embodied energy. Yes, a company can do an LCA, but they are just part of a production chain. LCA has its boundaries and often does not look at this whole process. When thinking of solutions for sustainability issues, this is something that should not be overlooked. You have to think of the materials, users, life cycle, and second life. Here she provided an example of the construction world, where a lot of energy goes into acquiring the materials. Essential here are the choices made after the LCA.

Geanne van Arkel stated that LCA is not necessarily complex to communicate. Just like in calories on food products, impacts can be summarized. CO₂ could be a good indicator to do this, and is often linked to other impacts in LCA anyway through the impact equivalents.

A strong point of LCA is that by just using it yourself and looking at your own products, you are already optimizing your production. Transparency is very important, she called it radical transparency. Consumers must be able to compare products. This leads to selection of the best ones, and innovation in every field. It is essential for the future. EPD is a solution for this need for transparency. By adding up scores companies cannot choose to tell consumers one good aspect, and market it, and hide the other many bad aspects.

She concluded with an anecdote about someone that asked her whether people are actually interest in sustainability. She said that people do have an interest. If a product is the same price and quality, they will need something else to choose from. Then they will pick the one that is most sustainable. However, at this point we are losing the opportunity to make this choice, as there is no transparency. Most people think of solutions to environmental issues, but we must also think about performance. How can we optimize what we already have?

JEROEN GUINÉE, LEIDEN UNIVERSITY

Jeroen Guinée has been mostly working on the development of the LCA method from a scientific point of view. Additionally, he has been developing LCA as a tool for industry and the EU, by the hand of different cases and by developing a Handbook for performing LCAs. Applications of LCA, he said, differ between different areas such as design, strategic decisions, or ecolabeling.

It is important to share LCAs of different products of the same category, and thereby map products. He underlined the importance of the solid science behind LCA, and that uncertainty must be addressed. He mentioned that normalization adds a certain amount of subjectivity to the LCA. This is sometimes done because of tradeoffs that have to be made between impacts. He mentioned here that LCAs which include social parameters are often less solid because of the subjectivity involved.

LCA does lead to improvements, but are not the sole solution to bigger environmental issues generally. He illustrated this by saying that production is indeed optimized through LCA, but that the environmental issues at hand are bigger. An example of companies he worked with is Forbo, a flooring company that implemented his handbook. Additionally, he worked with Procter and Gamble to optimize their production.

There are plenty of examples of bad LCAs out there. Mistakes are often made during the allocation phase, where the preferences of ISO are very clear, but there is never a single way to use it. This requires a lot of expertise in the field. As an example, there is always a problem with byproduct allocation. This comes with the problem that it injects some subjectivity from the researcher. Despite his earlier comment that the objectivity and science behind the method must be solid, this is an inevitable limitation to an LCAs objectivity.

Finally, this subjectivity brings with it another problem. When a government orders a reduction in greenhouse gas emissions, companies start reacting to this. They start looking for better options, but also have to quantify this. There has to be some kind of proof that they did what they were supposed to do, or at least are improving the situation. LCA is one of the tools that can be deployed to measure these improvements. However, when it becomes law that certain technologies cannot exceed certain values, money is involved, and an LCA must be lawsuit proof. One can imagine that a reduction of subjective choices is desirable in this case. When a high level of comprehensiveness is required LCA like this, the results become more complicated. This, in addition to a cost perspective and the subjectivity of a management system that has to weigh their decisions can lead to an overflow of information, which negatively influences the whole process.

DR. KRISHNA MANDA, UTRECHT UNIVERSITY

Krishna Manda told me firstly about the use of LCA, he described four cases for which the tool is used. During the research and development phase to compare between different alternative production routes and different configuration of products, during the business development phase for the most strategic product, during the investment phase and during the competition and marketing phase. Here, it is important to look at some marketable attributes that pop up during an LCA, and find the product's strong points in terms of environmental sustainability.

He said that it is near impossible to present all impacts to a management team and expect them to remember it and be able to interpret it usefully. Instead, he opts for simplification of the results. Often, CO2 is a go-to example of something that management will be able to value. People already know about the concept, and with some luck the impacts it has on our environmental. Therefore this impact is used a lot. Additionally, one can look at the most relevant impact categories. Not every product has an impact on all categories. However, this is something often already done during an LCA, where impact categories are chosen, and potentially leaves the researcher still with more than one message. Since it is difficult for management to understand all impacts, the LCA expert needs to present the trade-offs between most relevant impacts. This is very relevant to avoid burden shifting.

A final method Krishna Manda mentioned was to look at what the customer values. Ultimately, LCA is often used to add marketable value to a product. One can present the less important categories later in a presentation, brief or report, and not all information at the same time as a scientific paper would do. It is all about communicating the information in a smart way.

Even though there are several simplification methods, he pressed the importance of transparency throughout. A product might score well in one category, and bad in another, it is important that all are communicated at some point. This ultimately leads to tradeoffs made by the final decision makers, the job of an LCA expert is to provide the clearest overview possible. This transparency is also important towards the customer. A product might be marketed because of its great value for CO2 reduction efforts, a company should be clear if it also contains heavily intoxicating chemicals on a local scale towards its customers. This is also a job for the LCA expert to make clear.

All the above looks like the management layers of a company have no idea about sustainability and the impact their product has, and that is likely the case. However, they do understand that the subject is complicated and requires some attention. It is therefore important as an LCA researcher to ask yourself why they should be interested. The answer is, is that it is all about value creation. A business can change its production processes because of risk, economic factors, or compliance to laws or innovation opportunities. An LCA practioner should try to find the relevant aspects to assist the management in decision-making with the language of management such as risks, regulations, opportunities, costs, competitive advantage etc.

LCA is mainly used as a business support function. Once an LCA is done for a product, it can be used to raise awareness in the company about sustainability and serve as a business integration method. When one tries to do this, it is important to provide context to the client. Before doing an LCA, it is important to indulge in the local social conditions. One should first get to know the company, and its business culture. Who wanted this LCA? Who is participating? Often times the relationships and wishes of people already surface during this phase. Then, when you perform the LCA, you can target the right people to make the change. Krishna Manda referred me to his PhD thesis here, in which he described a detailed model to do this.

LI SHEN, UTRECHT UNIVERSITY

When I interviewed Li Shen we started talking about her LCA research on PET bottles, and the two different technologies used for recycling. Chemical recycling is of superior quality, but takes considerably more energy. The other technique, technical recycling, takes less energy but colors the PET darker. This is a problem for marketing purposes as people will not want to buy darkened PET bottles. The LCA showed that the clear, chemical recycling was worse environmentally. However, she mentioned, from an academic point of view this was a very interesting process to look into with an LCA. An LCA is time consuming, it takes a lot of effort and could take months at the minimum. Therefore, there are also a lot of bad LCAs out there by companies that do them in weeks or days even, these are not scientifically sound LCAs.

We then talked about Lenzing, a fiber company that has had sustainability thinking in the company from the start. However, the LCA showed that in some impact categories, their product was of superior properties but scored bad in three out of nine. One would say you cannot present this message to your customers. Because of this an internal debate had taken place whether the researchers were actually allow to publish and, extraordinarily, they were. The client in this case apparently chose transparency and superior property. Sales were on the rise after the publication of the LCA, which was an interesting learning experience for the LCA experts too.

When she does an LCA, she presents it many times to different teams within a company, but also externally. Not all departments have time to read everything she publishes, and the science really is only useful for an academic audience. Management wants a conclusive graph, with a strong main message to tell their clients. There are often different departments with different interests too. The research and development department often reads more than the upper management layers. If a company has a sustainability department, they want to read everything because they are the people that have to answer difficult questions from clients. The way to communicate the whole LCA is a conclusive graph is very challenging, since in science there is never a black and white story, but they want a black and white story.

Li Shen told me she doesn't mind how many people read the report really, as long as it is used in the right way. Besides, for her personally the academic interest is much higher anyway, and as she said before, they are not interested in the academic details. The PET bottle recycling case was fascinating. Management people also need to compare prices and processes, which is beyond her interest really. However, in LCA you can do it up to the point of analysis, or you can add an extra weighting and normalization step, where you take the subjective values of clients and input those into the final results. This leads to a single score output which are very useful for communication. Scientists often avoid this step, as it introduces subjective values into an otherwise as objective as possible research.

We got back to the topic of Lenzing, where she told me that by doing an LCA, they had started a chain reaction within their group of branches. They are a relatively small player in the apparel industry, but they used their LCA to point out that, although our product is not perfect, the cotton industry is much worse. This provokes a reaction from the cotton industry. The cotton industry decided to hire their own LCA experts and set into motion a lobbying apparatus. This is how they think, in competitive advantages. The ultimate outcome of this was that the cotton industry is now reducing their chemical use, one chemical for instance caused ninety percent of the bad impacts, and they are requiring suppliers to use less of it now. So this shows that the initial LCA by a relatively small player can have a much wider impact than just the research itself. A relatively old and traditional market like textile would not have started this themselves.

NIELS JONKERS, IVAM

Niels Jonkers (IVAM) works mostly with commercial assignments which concerns the calculation and modeling of environmental impacts . His expertise lies in waste management systems but he has worked in other fields as well. Sometimes he works for branch unions, which consist of several competitors with a single question. LCA, he said, is mostly a way of communication. Clients almost always want a simple answer, a single score to base their decision on. The trick to still implement some depth and relevance to the research when trying to present a single score is to add some nuances and emphasis on the process and the story of a product, e.g. in a discussion chapter. You have to fashion it in such a way that even though you are presenting a single score, the most important points will still surface and gain the attention of the decision makers.

Often Niels Jonkers presents a report, but sometimes also an Excel-based calculation tool so that the client can adjust the data themselves. They can see how the model works and what the assumptions are between different products, and can shift parameters and come to their own conclusions rather than looking at fixed results. This provides engagement and therefore often creates deeper insight, and more informed decision making.

As an example of an LCA he experienced some difficulties with he presented the case of an organic waste tool for municipalities. He had to measure the environmental performance of waste processing systems. A large disadvantage here was that the tool proved to be too complicated. Companies found it was too much work to fill out the parameters in the tool. In this case, a simpler tool could have worked better, although it may describe the reality less accurately. He also works with the Dutch National Environmental Database for construction materials (Nationale Milieudatabase). This project was set up by the government to allow the calculation of the impacts of all construction materials and practices in a consistent way. The way this works, he explained, is that companies can hire an LCA consultancy company which reviews the calculations for their materials and processes, and then enter this database. In the Netherlands, by law, a construction company must have an environmental assessment of a project ready before they can start on it.

We also briefly talked about the difficulties companies can have interpreting results when they try to compare it to other factors such as budget. He explained that one way is by shadow prices: monetizing the costs of repairing the damage done by your product, but that it remained an imperfect way to do this. Another difficulty is the way in which less well-known impacts are valued. CO₂ reduction was often seen as important, and decisions are more often adjusted because of this parameter than others. Another difficulty that increasingly plays a role is land use.

We ended our conversation with another example of an LCA that posed some problems in the decision making phase. This one was about weed control methods (on pavements) used by the government. There are several options to do this, e.g. hot water, hot air or herbicides. After careful calculation it was shown that, because of long-term impacts on a large scale, hot water and hot air were found to score worse than the use of herbicide. Chemicals therefore, from an environmental point of view, would be the best option. This because certain effects of small amounts of poison would dissipate fairly rapidly on a local scale. The energy requirements of heating hot water for this far exceeded the effects of local poisoning. There was outrage and disagreement about the results of the study, and finally the use of herbicides was banned anyway, even though according to the calculations, it was the better option . This, he said, showed that the objectivity you have is only within your own calculation system. The LCA method considers 'the big picture', and focuses mainly on long-term and large scale damage. When societal groups are more worried about temporal smaller-scale environmental issues, they feel their concerns are ignored by the calculations. Both the big picture information provided by LCA and local concerns should be considered in the decision making process.

We ended our conversation with a talk about the future of LCA, and he said that there would be an equal amount of LCA required, it was not that much on the rise. Sustainability is becoming more and more important, but LCA is not the only tool to analyze sustainability. Additionally, there are problems LCA cannot (yet) address, where he gave an example of the plastic soup in the ocean. LCA is first and foremost a tool for communication and awareness.