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EVALUATION OF LIFE CYCLE ANALYSIS CASE STUDIES: FINDINGS FOR APPLICATION AND FURTHER DEVELOPMENT

A. Rosner, C. Hollauer, D. Kammerl, M. Omer and M. Mörtl

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1. Introduction

A large proportion of global ressource consumption and emissions are caused by all kinds of products worldwide, in both consumer and business markets. In order to reduce or even eliminate the negative environmental influence of products, the development of sustainable products is important. Driven by climate change and worldwide resource scarcity, sustainable product development is currently playing an important role and will continuously gain further importance.

One possibility to assess the level of sustainability of products during the whole life cycle is by conducting life cycle analyses. The concept is also known and applied in Systems Engineering, where life cycle thinking is used to derive important input for the development of future products, such as the formulation of new or updated requirements [Walden et al. 2015]. Three different method variants of life cycle analyses can be distinguished, each representing one of the three pillars of sustainability as defined in the Brundtland Report (ecologically, economically, socially) [Brundtland 1987]: ecological life cycle analyses are known as Life Cycle Assessment (LCA), economic ones as Life Cycle Costing (LCC), and social ones as Social Life Cycle Assessment (SLCA).

The main problem in the assessment of a product with one of these three method variants is the apparent lack of a consistent and clear procedure in applying these different life cylce analyses. Even though approved norms and guidelines for the individual method variants do exist, these norms and guidelines do not include a detailed description of the methodology and do not fix any specific methods for the four life cycle analysis phases. These difficulties regarding the methodical procedure for all three method variants are a reason for uncertainty concerning the right execution of life cycle analyses. Practitioners therefore often do not know what they must pay attention to when conducting a life cycle analysis [Heijungs et al. 2010]. Up to now experience with different method variants has been limited. Hence there is a lack of best practices and findings that would be helpful in conducting life cycle analyses [Guinée et al. 2011].

This paper intends to give a comparative overview of the current state of research and application concerning life cycle analyses and to subsequently identify research issues. For this, first a general comparison of the application of the three method variants is given, followed by a more detailed look into the application of the most common method variant LCA. For this, life cycle analysis case studies (of the method variants LCA, LCC, and SLCA) are first identified in literature and subsequently coded, analyzed and evaluated according to different criteria. The findings serve as an applicable support for practitioners (i.e. good/best practices) on the one hand and identify potentials for the advancement of assessment methods on the other hand, i.e. sharpen the need for future research activities.

The structure of the present paper is as follows: after the introduction (chapter 1) a literature review on sustainability and life cycle analyses is given (chapter 2). In the third section the research model of the work will be explained (chapter 3). In the following chapter the results of the study will be presented (chapter 4). Finally the summary and discussion of the results lead to the conclusions of the study (chapter 5).

2. Life cycle assessment background

Although the term sustainability originally comes from forestry, the present understanding of the term differs from the original. The current understanding is primarily based on the Brundtland Report from 1987 because the principle of sustainable development was first formulated in that report: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." [Brundtland 1987] The report was written by the World Commission on Environment and Development (Brundtland Commission) of the United Nations and aimed at providing an opportunity for sustainable and ecological friendly development. Three pillars must be considered for sustainable development: economic growth, environmental protection, and social equality [Brundtland 1987].

For designing sustainable products in practice, the possibility to assess the degree of sustainability is of paramount importance. Singh et al. [2009] give an overview of existing methods for supporting sustainability assessment. One of the most important methods described by them is the life cycle analysis. The integral life cycle analysis framework that considers the three pillars of sustainability (ecologically, economically, socially) at the same time is called Life Cycle Sustainability Assessment (LCSA) and was developed by Klöpffer [2008]. In that framework the three life cycle analyses (LCA, LCC and SLCA) are executed separately but within the same system boundary and functional unit.

Based on the concept of Klöpffer [2008], UNEP (United Nations Environment Programme) and SETAC (Society of Environmental Toxicology and Chemistry) published a guideline [Valdivia et al. 2011] that is meant to pave the way for a standardized Life Cycle Sustainability Assessment. The guideline proposes to use the same four phases of LCA in principle also for the method variants LCC and SLCA. Until now there is a lack of published practical literature in which the integral LCSA-framework (with its three method variants) is applied to a certain product.

The currently most widely used method variant LCA was developed in the USA in the 1970s and also used in Europe shortly thereafter [Klöpffer 1997]. In a LCA life cycle analysis the inputs and outputs plus the potential environmental impacts of a product system are compiled and evaluated during the product's whole life cycle [DIN EN ISO 14040 2009]. Based on the groundworks of SETAC which published a first LCA guideline in 1993, the International Organization for Standardization (ISO) started to develop standards with the aim of standardizing the methodical procedure for the method variant LCA in 1994. Between 1997 and 2000, at first the ISO standards 14040, 14041, 14042 and 14043 were published. In 2006, these first standards were replaced by the ISO standards 14040 and 14044. ISO standard 14040 deals with principles and framework of LCAs, ISO standard 14044 with requirements and guidelines [DIN EN ISO 14044 2006], [DIN EN ISO 14040 2009].

Life Cycle Costing (LCC) was first mentioned in the 1930s in a tractor delivery contract in the USA. According to Ciroth et al. [2011], in a LCC life cycle analysis all costs related to a product over the product's whole life cycle are assessed. Today two types of LCCs can be distinguished: Conventional LCC (its original form) and Environmental LCC. Whereas Conventional LCC can be carried out independently from the method variants LCA and SLCA, the Environmental LCC can be realized in combination with a LCA or an integral LCSA [Valdivia et al. 2011]. The Environmental LCC therefore must be compatible with the two other method variants LCA and SLCA [Ciroth et al. 2011]. In this paper, the focus will be on the procedure method Environmental LCC as it can be combined with the two other method variants within the integral LCSA-framework. The concept of Environmental LCC was worked out by SETAC LCC Working Group. In 2003 it started to develop a first monograph [Hunkeler et al. 2008], before a SETAC guideline entitled „Environmental Life Cycle Costing: A Code of Practice" [Swarr 2011] was published in 2011. This guideline shall serve as a basis for a subsequent ISO standard which should orientate itself at the existing ISO standards 14040 and 14044 of the method variant LCA [Swarr et al. 2011].

The youngest of the three method variants is the Social Life Cycle Assessment (SLCA) which considers the social dimension of the three sustainability pillars. SLCA can be defined as a social and socio-economic LCA with the aim of assessing the social and socio-economic aspects of products plus its potential positive and negative impacts throughout their life cycle [Benoît and Mazijn 2009].
Based on the integral LCSA-framework of Klöpffer [2008], UNEP and SETAC develop a guideline for the method variant SLCA so that it can be combined with the method variants LCA and LCC. These „Guidelines for Social Life Cycle Assessment of Products" [Benoît and Mazijn 2009] suggest a twofold classification for the assessed social criteria: stakeholder categories and impact categories.

3. Methodology and research questions

The objective of this paper is to give an overview of the current practice of LCA, LCC, and SLCA. For this purpose, life cycle analysis case studies collected from literature are coded, analyzed and evaluated. The collected case studies range from simple (mobile phone charging cable) to complex products (offshore windturbine)[1]. The knowledge obtained contributes to identify good or best practices for practitioners and to identify potentials for the advancement of life cycle analyses in research.
The research questions (RQ) in this paper (cf. section 4) have been developed based on an initial, exploratory literature survey concerning the current practice and limitations of life cycle analysis approaches. The intention of the presented work is to contribute to a better understanding concerning the application of life cycle analysis methods as well as to further sharpen and triangularize the need for future research activities. Hence the research questions pertain to aspects such as e.g. the diversity of the applied methods, the forms of support most oftenly used, the most often used impact categories and the date sources tapped in order to conduct the analyses.
The RQs will be stated and answered in detail in section 4, their structure consisting of two levels (cf. Figure 1). Level 1 comprises a comparison of the method variants LCA, LCC and SLCA, investigating the degree of standardization of the applied methods (and thus evaluating the influence and importance of existing standards) as well as mapping the overall spectrum of applied methods in the sample group, in order to identify the degree of consolidation or diversity of the applied methods (cf. RQ1 & 2). In level 2, a detailed analysis of just the method variant LCA is conducted. This structure was chosen since an in-depth comparison of all three method variants does not seem meaningful for all collected variables. The method variant LCA is analyzed in more detail because in practice it is of currently higher importance than the two other method variants LCC and SLCA [Heijungs et al. 2010], [Guinée et al. 2011]. Another reason for the focus on LCA is the existing standardization of that method variant through the ISO standards 14040 and 14044. This standardization, which does not (yet) exist for the two other method variants LCC and SLCA presents an interesting opportunity for analysis as the adherence to the ISO specifications can be investigated based on the case studies (cf. RQ1). It can be seen in Figure 1 that the research questions of level 2 are further separated into three clusters: „ISO-14040/14044-conformity", „Further findings of the case study analysis" as well as „Success factors and challenges".
The overall research methodology applied in this paper to answer the RQs followed the methodical approach of Eisenhardt [1989] and Korpi [2008] and consisted of five methodical steps. As can be seen in Figure 1, at first the sample creation and the classification of criteria were executed simultaneously. After these two initial steps, the data of interest was first collected and then analyzed. Finally some of the results obtained were evaluated statistically. A more precise explanation of the individual steps follows.
The aim of the sample creation was to create a sample of life cycle analysis case studies from literature as representative as possible, enabling well-founded answering of the stated RQs. Case studies of all three method variants (LCA, LCC und SLCA) were selecetd. As recommended for case study research [Eisenhardt 1989], the case studies in this paper were not chosen randomly but were selected based on certain criteria (e.g. belonging to method variants). The chosen sample size was 45 case studies (25 LCA, 10 LCC, and 10 SLCA case studies), with the numbers reflecting the focus on the investigation of LCA case studies and representing a compromise between thoroughness of analysis and the result

[1] A complete list of case studies identified from literature is available at request from the authors.

effort. In order to ensure an up-to-date examination of life cycle analyses, the period under considertation ranged from 2005 to 2015.

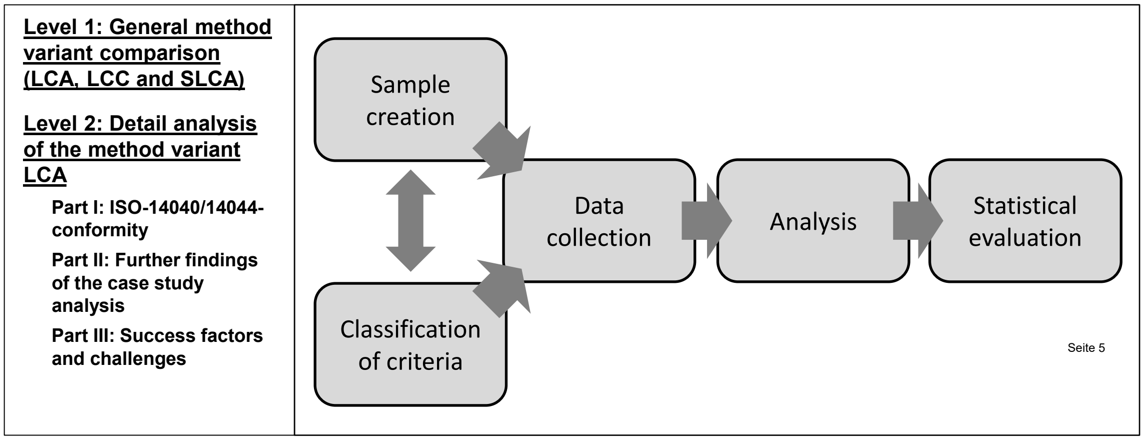


Figure 1. Research methodology

The required criteria for the data collection and analysis were developed simultaneously with the sample creation. This classification of criteria should determine all criteria (i.e. characteristics, variables) that are necessary for answering the RQs. Therefore, a classification scheme was created in which all criteria and their attributes were defined, serving as the basis for data collection in order to answer the RQs.

Following the sample creation and the classification of criteria, the data of interest was collected. At the data collection step, the case studies of the sample were analyzed separately to identify the case study specific attributes of the different criteria. The collected information was then summarized in an Excel file and subsequently analyzed in the following step.

In the last step of the research methodology some of the results obtained were evaluated statistically, in order to better assess the significance of the selected results. Since a statistical evaluation makes sense especially for quantitative criteria, it was applied to the conducted regression analyses. With these regression analyses both the strength and the direction of the linear correlation between different quantitative variables was measured. In order to check the quality of the regression function the following statistical characteristics were used: the regression function y, the coefficient of determination R^2, and the value of the F-test F [Backhaus et al. 2011].

4. Results

After explaining the structure of the research questions (RQ) and the research methodology in the previous chapter, this part of the paper will outline the research questions and the results of the study in detail.

4.1 Results level 1: general method variant comparison (LCA, LCC and SLCA)

In the first level of the research questions, the three method variants LCC, SLCA, and LCA were compared in general. Especially the procedure methods used in practice were of particular interest.

RQ (1): How large is the share of case studies in the different method variants LCA, LCC and SLCA which refer to the ISO standards 14040 and 14044?

The answer to research question (1) can be seen in the upper row of pie charts of Figure 2. The figure shows that 84% of all LCA case studies, 20% of all LCC case studies and 80% of all SLCA case studies refer to the ISO standards 14040 and 14044 in their methodical procedure (sum of the attributes "yes", "no, but implicit yes", and "partly"). The high value of the method variant LCA is insofar obvious as the ISO standards 14040 and 14044 were developed above all for the application in LCA case studies. However, the ISO standards also describe the possibility of using elements of the methodology for the method variants LCC and SLCA. When looking at those two, a great difference between the percentage values of the method variants LCC and SLCA can be observed. Whereas only 20% of the LCC case studies under analysis refer to the ISO standards, on the other hand at least 80% of the SLCA case studies do so. At 80%, the share of SLCA case studies which refer to the ISO standards 14040 and 14044 is almost as high as the share of LCA case studies at 84%. It should be distinguished, however, that all of these 84% LCA case studies refer to the ISO standards completely (and not only to some extent or "partly"), 64% of them explicit and 20% implicit. When looking at the method variant SLCA, on the other hand, the total percentage of 80% refers to the ISO standards only "partly". This attribute means that there were used other procedure methods than the ISO standards. Nevertheless, these procedure methods are based on the ISO standards and are very similar to them in their fundamental structure. These other procedure methods will be further examined in RQ (2).

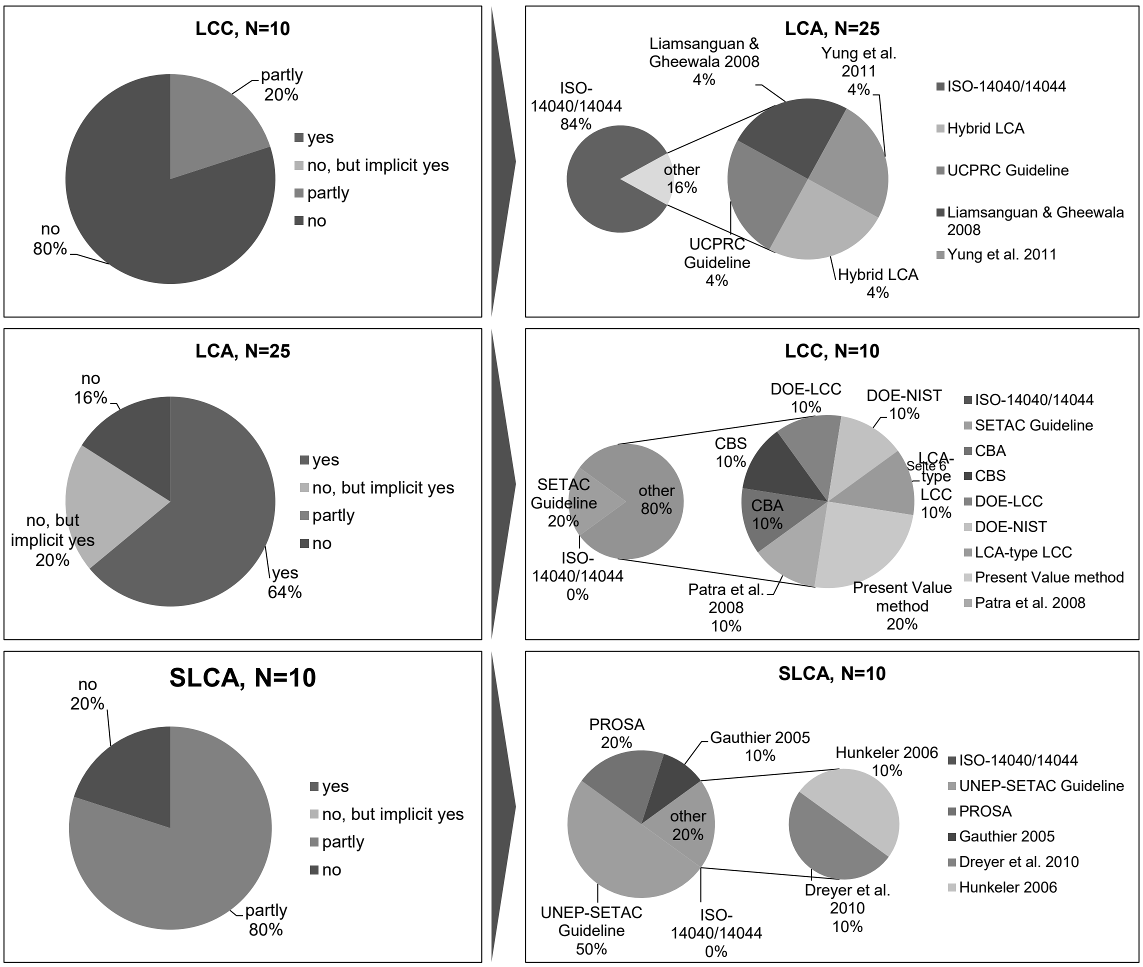


Figure 2. Reference to ISO-14040/14044 and other procedure methods

RQ (2): Which other procedure methods are used for conducting LCA, LCC and SLCA case studies besides the ISO-14040/14044 procedure method?

The answer to research question (2) can be seen in the lower three pie charts of Figure 2. The figure shows all procedure methods used in the case studies. The (smaller) main circle in each pie chart lists the procedure methods based on the ISO standards 14040 and 14044. This contains the ISO-14040/14044 procedure method itself (includes explicit and implicit mention) as well as those procedure methods that refer to the ISO standards only "partly". The extracted circle to its right, however, mentions all procedure methods which do not refer to the ISO standards (attribute "no" in RQ (1)). The result of research question (2) is a vast amount of different procedure methods.

4.2 Results level 2: detail analysis of the method variant LCA

In the second level of the research questions, the method variant LCA was analyzed in detail, wheras the method variants LCC und SLCA weren't considered. The second level consists of three parts: „ISO-14040/14044-conformity" (RQ 3 and 4), „Further findings of the case study analysis" (RQ 5, 6, 7, 8, and 9), and „Success factors and challenges" (RQ 10 and 11). The answers to the research questions will be presented in the following sections, structured by the individual research questions in ascending order.

RQ (3): To what percentage do the LCA case studies fulfill the described procedure of the ISO standards 14040 and 14044?

The answer to research question (3) can be seen in Figure 3. The left chart shows how many of the 25 case studies from the sample fulfill a certain ISO-14040/14044-conformity in percent. The ISO-14040/14044-conformity indicates how many of the 10 ISO criteria are fulfilled or not fulfilled by a certain case study. In order to decide if an examined case study fulfills the ISO criteria "for the most part" and therefore is ISO conformal or not, a threshold value of 70% was chosen. This value was determined at this level because it seems suitable to decide if something is fulfilled "for the most part" or not. Consequently, all case studies which are on the right side of this line and therefore fulfill at least 70% of the ISO criteria are reffered to as "ISO conformal". Those case studies left of this line, however, are reffered to as "not ISO conformal". As can be seen in the right chart, hence 72% of all examined case studies are "ISO conformal" and 28% are "not ISO conformal". It should be noticed that this result contains a high sensitivity because after all 7 of 25 case studies have an ISO-14040/14044-conformity of exactly 70%. If the threshold value for the ISO-14040/14044-conformity would be chosen higher than 70%, those 7 case studies would be reffered to as "not ISO conformal".

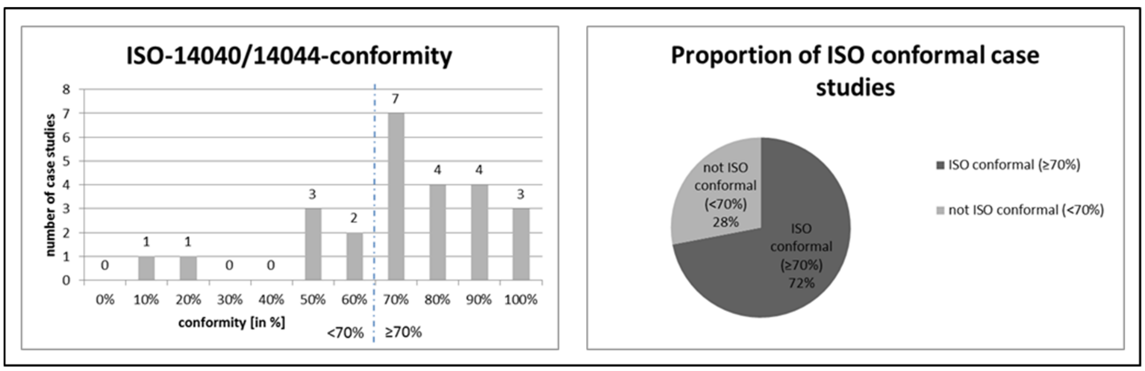


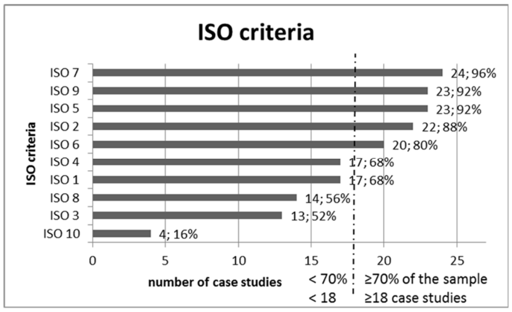
Figure 3. ISO-14040/14044-conformity

RQ (4): Which components of the described procedure in the ISO standards 14040 and 14044 are fulfilled by at least 70 percent of the LCA case studies?

This research question shall indicate which components of the ISO standards are applied in practice and which not. In order to answer the research question, the already known threshold value of 70% from RQ (3) is used. The response to research question (4) can be seen in Figure 4. The figure shows for each of the 10 ISO criteria, how many of the 25 case studies from the sample fulfill the corresponding criteria. It can be noticed that there are great differences between the different criteria.

RQ (5): Which LCIA methods are used in the impact assessment phase?

The answer to research question (5) can be seen in the left chart of Figure 5. The chart lists for all LCIA methods used how often they were applied in the sample. It can be noticed that especially the LCIA methods "CML" (11 case studies) and "Eco-Indicator 99" (9 case studies) are used very commonly. Other methods seem much less popular.



ISO criteria - legend:

Criterion	Name	Explanation
ISO 1	Goal	application, reasons, audience, public
ISO 2	Scope	function, functional unit, reference flows, system boundary, data quality requirements
ISO 3	Life cycle phases	raw material extraction, production, use, disposal / recovery
ISO 4	Inventory analysis	quantification of relevant inputs and outputs of the product
ISO 5	Impact assessment 1	selection of impact categories, category indicators and characterization models
ISO 6	Impact assessment 2	classification and characterization
ISO 7	Interpretation 1	identification of significant issues
ISO 8	Interpretation 2	completeness, sensitivity & consistency check, conclusions, limitations, recommendations
ISO 9	Reporting	effective report in an adequate form
ISO 10	Critical review	by internal/external expert or by a panel of interested parties

Figure 4. ISO criteria

RQ (6): Which data sources and softwares are used for conducting LCA case studies?

The answer to research question (6) can be seen in the middle and right chart of Figure 5. The middle chart lists all data sources (including databases), the right chart all softwares used in the case studies from the sample. Data sources include, in addition to several "databases", also "manufacturer's data" and "other" data sources. The chart shows that the "Ecoinvent database" (15 case studies) is the most frequently used database, clearly followed by the "GaBi database" (4 case studies). When looking at softwares, it can be noticed that the software solutions of "SimaPro" (9 case studies) and "GaBi" (5 case studies) dominate, no further specific software is used to greater extent.

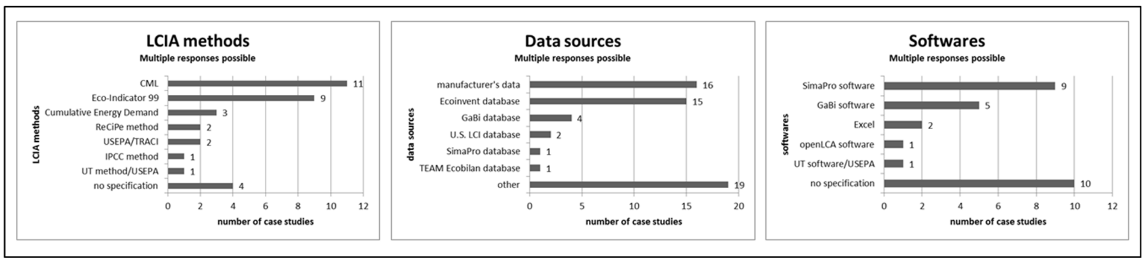


Figure 5. LCIA methods, data sources and softwares used

RQ (7): Which impact categories are used for conducting LCA case studies?

The answer to research question (7) can be seen in the left chart of Figure 6. The figure shows how often the different impact categories are used in the case studies. It should be noted that only those impact categories are listed separately in the figure which were declared as most important impact categories ("baseline impact categories") in the „Handbook on Life Cycle Assessment" by Guinée [2002]. All additional impact categories that are used in the case studies, are specified as "other" impact categories. It can be noticed that all "baseline impact categories", with one exception, are used in more than half of the case studies. Even if "other" impact categories can be found in 21 of 25 case studies, no individual of these is used in a considerable number of case studies (more than three case studies).

RQ (8): Which life cycle phases are considered for conducting LCA case studies?

The answer to research question (8) can be seen in the middle chart of Figure 6. The figure shows which part of the examined case studies does consider a certain life cycle phase. The following life cycle phases were taken into account in the data collection: "raw material extraction", "production", "transport and distribution", "use", and "disposal / recovery". The particular of the "raw material extraction" phase is that it is sometimes considered as an independent phase (deep grey bar) and sometimes as a part of the "production" phase (light grey bar). It can be noticed that all 25 case studies from the sample take into account the "production" phase. The "raw material extraction" phase and the "use" phase are considered by 22 (15 + 7) and 20 case studies, respectively. The "disposal / recovery" phase (15 case studies) and the "transport and distribution" phase (14 case studies) are considered less frequent.

RQ (9): What are the reasons for conducting LCA case studies?

The answer to research question (9) can be seen in the right chart of Figure 6. The most common reason for conducting LCA case studies is to compare several products with each other (15 case studies). Another important reason is to identify potential product improvements (14 case studies) which can be realized when further developing the product. Furthermore, LCA case studies serve as a scientific basis and support for future life cycle analyses (11 case studies). After all, 6 authors mention environmental protection as a motive for conducting LCA case studies.

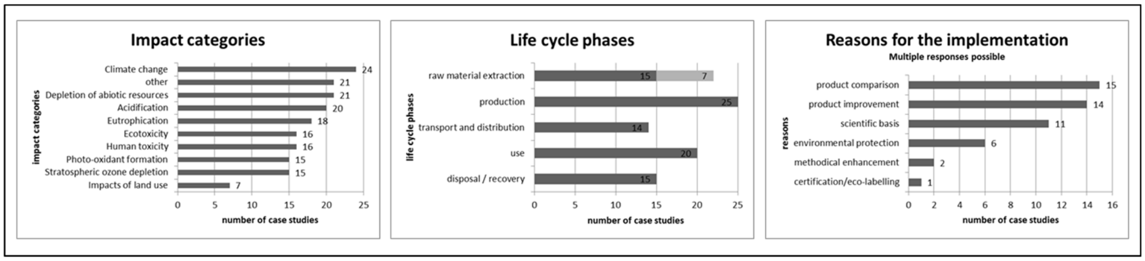


Figure 6. Impact categories, life cycle phases and reasons for the implementation

RQ (10): Which success factors for the implementation of LCA case studies are mentioned by the authors of the case studies?

The answer to research question (10) can be seen in the left chart of Figure 7. The left chart indicates all identified success factors and how often they were mentioned in the case studies. The intention of the RQ is to identify potentials as well as deficits (in conjunction with RQ10), from which requirements for further development can be derived, which need to be adressed in order make LCA more useful and facilitate its application in practice. A successful LCA is defined as a LCA which leads to relevant and usable insights into the lifecycle impact of a product. In 17 of 25 case studies, no discernible success factors were identified by the authors of the case studies. In the remaining cases, only the success factor "LCA as a practical tool" is mentioned more than once, indicating that the LCA methodology has proven to be suitable for the objectives of the case study. "LCA in early planning phase" indicates that the application of LCA needs to be enabled early in development projects, in order to have an impact on the current product development.

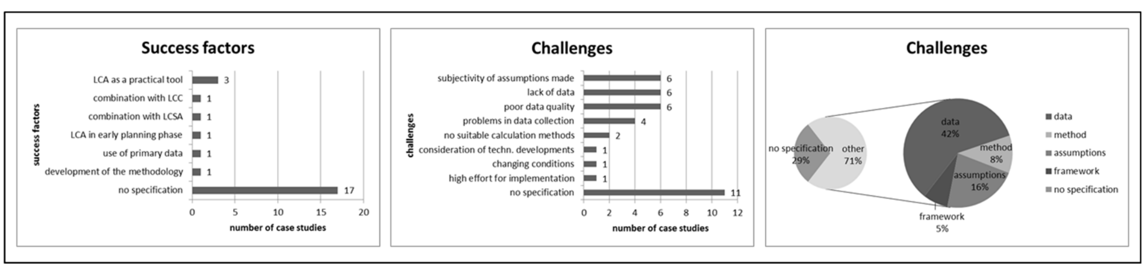


Figure 7. Success factors and challenges

RQ (11): Which challenges for the implementation of LCA case studies are mentioned by the authors of the case studies?

The answer to research question (10) can be seen in the middle and right chart of Figure 7. The middle chart indicates, analogous to the left chart, all identified challenges and how often they were mentioned in the case studies. In order to summarize the identified challenges to thematic topics, they are assigned to the categories "framework", "method", "assumptions", and "data" in the right chart. By far the most important challenges when conducting LCA case studies are challenges concerning data (42% of all mentions, including the attribute "no specification"). Among these data challenges are "lack of data" (6 mentions), "poor data quality" (6 mentions), and "problems in data collection" (4 mentions). Challenges with assumptions constitute the second most important topic (16% of all mentions). The challenge "subjectivity of assumptions made" (6 mentions) describes the problems that arise when appropriate assumptions have to be made (often at the beginning of the analysis). Although

5. Discussion and outlook

As explained in the introduction, uncertainty on how to implement and conduct life cycle analyses constitutes a research gap. In order to reduce this uncertainty, this study gives both a general comparison of the three method variants LCA, LCC, and SLCA as well as a detailed analysis of the method variant LCA. The knowledge obtained can serve as a support for practitioners on the one hand and helps to identify potentials for the advancement of life cycle analyses in research on the other hand.

The general comparison pointed out differences between the method variants LCA, LCC und SLCA: the most prevalent procedure method for the method variant LCA is the ISO-package (ISO 14040 and 14044). In the method variant SLCA, the UNEP/SETAC guideline dominates. Only when looking at the method variant LCC, none of the existing procedure methods (including the LCSA-compatible SETAC guideline) prevails so far.

The detailed analysis of the method variant LCA demonstrated that the majority of the LCA case studies turned out to largely comply with the specifications of the ISO standards 14040 and 14044. Half of the ISO-criteria examined (RQ5) were fulfilled (considerably) less often by the analyzed case studies. Further development should focus on these aspects, defining them in more detail in the ISO standards, and developing/giving further methodical support. The analysis pointed out the dominance of certain tools and calculation methods. Despite a wide range of existing LCIA-methods, databases and softwares, only one or two types of these tools are prevalently used in practice. In the authors' opinion, these tools and calculation methods which have proved suitable in practice and are used predominantly, could be included in the ISO standards 14040 and 14044 and be recommended for use. This measure would contribute to counteract the points of criticism of Heijungs et al. [2010], who attest the ISO standards to be incomplete, unclear and contradictory.

The identification of challenges (RQ11) came to the result that the availability of accurate data and making of appropriate assumptions are the main challenges when conducting LCA case studies. A possibility to cope with these challenges is to improve the databases and softwares used. As previously mentioned, these tools and calculation methods could further be included as recommendations in the ISO standards. Furthermore, the continuing trend of digitalization facilititates company access to real usage data of products. However, this in turn creates new challenges concerning the effective and efficient management and integration of this usage data in the development processes of future products, e.g. through its use in life cycle analysis.

Because of its broad application in practice, the UNEP/SETAC guideline for SLCA should be developed further towards an ISO standard with stringent methodical specifications, based on the existing ISO standards 14040 and 14044. The SETAC guideline of the method variant LCC, on the other hand, should be revised as a guideline with the aim of increasing its practical application in future, preparing further standardization.

A potential limitation of the presented results and the subsequent conclusions is the relatively small sample size investigated. The main reason for this sample size is the high temporal expenditure of analyzing each individual case study. The relatively small number of collected criteria for the LCC and SLCA case studies can represent another shortcoming. As mentioned already, the lack of comparability and the subsequent focus on LCA are reasons for that. A further limitation could derive from the fact that the case studies were selected based on certain criteria instead of randomly. This to some extent selective choice can lead to statistical bias which would not occur when considering the entire population. As argued above, justified interest in revising and developing the consisting standards and guidelines exists. Hence, it may be appropriate to further develop the conducted case study analysis and expand it to a higher level of detail, in order to further map the road towards a broader adoption of efficient and effective life cycle analysis.

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Christoph Hollauer, Dipl.-Ing., Wissenschaftlicher Mitarbeiter
TUM, Institute of Product Development
Boltzmannstraße 15, 85748 Garching bei München, Germany
Email: christoph.hollauer@pe.mw.tum.de