# Evaluation of environmental life cycle approaches


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## Abstract

Environmental policies focussing on a life cycle approach of products are integrated on a political level and adopted by societal stakeholders. These policies aim to promote the idea of Life Cycle Thinking – taking into account the environmental performance of systems throughout their life cycle. In order to provide sound information on the life cycle performance of a system, reliable methods need to be applied if the strategies are meant to be realised practically.

The objective of this thesis is to evaluate the suitability of different life cycle methods for applications of micro and macro level decision making in order to provide a sound basis for the principle of life cycle thinking.

The methods are selected as being representative and widely used for both decision-making levels taken into account and are assessed with regard to general, methodological and technical issues of importance in their application. For this purpose a comprehensive evaluation scheme is developed consisting of ten criteria and descriptive sub-criteria and aspects.

Compliance of the methods for each sub-criterion is evaluated by assessing their fulfilment with these aspects. Case studies are conducted in order to check the theoretical evaluation and provide additional insight into practical considerations.

An unambiguous result can be shown for micro level applications as process-based LCA shows a generally higher compliance with the considered criteria than any other method. On the macro level the result is revealed to be more diverse, none of the methods shows clear advantages in an overall evaluation but rather different strength and foci. The case studies confirm the evaluation on both levels for the most part, adding insight on which criteria might be most case specific and how they might be affected by practical conditions. This leads to the conclusion that specific conditions of an application need to be taken into account before deciding for one of the methods; especially for macro level applications.

The information given by this evaluation can provide valuable decision support for the method selection, either with regard to the methods evaluated in this thesis or as the basis for further method evaluations.

## Zusammenfassung

Umweltorientierte Strategien, die einen Lebenszyklusansatz von Produkten verfolgen, werden auf politischer Ebene integriert und von gesellschaftlichen Gruppen angewandt. Solche Strategien zielen auf die Förderung des Lebenszyklusgedankens ab, d.h. sie betrachten die Umweltleistung von Produkten über den gesamten Lebensweg. Um diese Strategien praktisch umzusetzen bedarf es zuverlässiger Methoden, die fundierte Informationen über die Lebenszyklusleistung von Systemen liefern können.

Ziel dieser Arbeit ist es, verschiedene Lebenszyklusmethoden hinsichtlich ihrer Eignung für die Bereitstellung einer gesicherten Grundlage bezüglich des Lebenszyklusprinzips für die Anwendung in Entscheidungsprozessen auf Mikro- und Makroebene zu bewerten.

Die ausgewählten Methoden sind repräsentativ für die Anwendung auf den betrachteten Entscheidungsebenen und werden in Bezug auf allgemein, methodisch und technisch bedeutende Fragen ihrer Anwendung bewertet. Zu diesem Zweck wird ein umfangreiches Bewertungsschema, bestehend aus zehn Kriterien und diese beschreibenden Unterkriterien sowie Aspekten, entwickelt. Die durchgeführten Fallstudien dienen der Überprüfung der theoretischen Erkenntnisse und stellen weitergehende Informationen zu praktischen Belangen bereit.

Für die Anwendung der Methoden auf der Mikroebene liefert die Bewertung ein eindeutiges Ergebnis, da die prozessbasierte Ökobilanz hier generell besser abschneidet als die anderen betrachteten Methoden. Auf der Makroebene ergibt sich ein breiter gefächertes Ergebnis, da keine der Methoden generell Vorteile in allen untersuchten Bereichen gegenüber den anderen Methoden aufweist. Die Methoden haben vielmehr unterschiedliche Stärken und Schwerpunkte. Die Fallstudien bestätigen diese Ergebnisse größtenteils und zeigen auf, welche der Kriterien besonders fall- und praxisabhängig sind. Daraus ergibt sich die Notwendigkeit, die spezifische Situation einer möglichen Anwendung in Betracht zu ziehen, bevor eine Entscheidung für eine der Methoden getroffen wird. Dies gilt insbesondere bei Anwendungen auf der Makroebene.

Die Erkenntnisse aus dieser Arbeit können eine nützliche Entscheidungshilfe bei der Auswahl von Lebenszyklusmethoden sein, sowohl in Bezug auf die hier untersuchten Methoden als auch als Basis für die Bewertung weiterer Methoden.

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## List of Figures and Tables

## Abbreviations

3R ...................... Reduce, Reuse, Recycling
AP...................... Acidification Potential
EAA .................. European Aluminium Association
EF ...................... Ecological Footprint
EIO-LCA........... Environmental Input-Output LCA
EIPRO ............... Environmental Impact of Product
ELCD ................ European Life Cycle Database
EP ...................... Eutrophication Potential
EPD ................... Environmental Product Declaration
EUEB ................ European Union Eco-labelling board
EW-MFA........... Economy-wide MFA
FAETP............... Freshwater Aquatic Ecotoxicity Potential
GTAP7 .............. Global Trade Analysis Project
GWP.................. Global Warming Potential
HIPS .................. High Impact Polystyrene
HTP ................... Human Toxicity Potential
IISI..................... International Iron and Steel Institute
IJLCA................ International Journal of Life Cycle Assessment
ILCD ................. International Reference Life Cycle Data
ILCD.................. International Reference Life Cycle Data
IO....................... Input-Output
ISO .................... International Organization for Standardization
LCI .................... Life Cycle Inventory
LCIA.................. Life Cycle Impact Assessment
MAETP ............ Marine Aquatic Ecotoxicity Potential
MFA .................. Material Flow Analysis
MRIO ............... Multi-region input-output
NMVOC............ Non-Methane Volatile Organic Compounds
ODP .................. Ozone Depletion Potential
PA 6.6................ Polyamide 6.6
PAH................... Polycyclic Aromatic Hydrocarbons
PE-HD............... Polyethylene High Density
PE-LD............... Polyethylene Low Density
P-LCA ............... Process-based LCA
POCP................. Photochemical Ozone Creation Potential

SERI .................. Sustainable Europe Research Institute
SFA ................... Substance Flow Analysis
STAF ................. Stocks and Flows Project
SUT .................. Supply and Use tables
SWOT ............... Strengths, Weaknesses, Opportunities and Threats
TETP ................. Terrestrial Ecotoxicity Potential
WIO ................... Waste Input-Output
WIOD ................ World Input-Output Database

# 1 Introduction

## 1.1 Background and Motivation

Environmental policies, which focus on a life cycle approach of products or wider systems, in general are integrated on a political level and adopted by societal stakeholders, e.g. industry or non-governmental organisations. These policies include the European Sustainable Development Strategy, the Thematic Strategy on the Sustainable Use of Natural Resources (TS Resources) or the Integrated Product Policy Communication all of which aim to promote the idea of Life Cycle Thinking – taking into account the environmental performance of systems throughout their life cycle [EC 2003, EC 2005, EC 2006]. In order to provide sound information on the life cycle performance of a system, reliable methods need to be applied if the strategies are meant to be realised practically.

Several existing methods are based on the principle of Life Cycle Thinking. They are applied both interchangeably and complimentary for different objectives and on different decision-making levels. Previous studies have given insight on strengths and limitations of these, see for example [SCHEPELMANN ET AL. 2008] and [MINX ET AL. 2007]. These studies focus on either very specific applications which means their results cannot be generalised or use a specific method as basis aiming to improve it by broadening it through the addition of other methods. Currently missing is a comprehensive and comparative evaluation of these methods on an equal basis. Such an evaluation would need to take into account the methods' different foci and provide results on their individual advantages through transparent criteria.

## 1.2 Objective of the Thesis

The present study aims to fill the gap in information described above. The overall objective of this thesis is therefore to evaluate a selection of life cycle based methods with regard to their suitability to different decision-making situations.

Such an evaluation needs to be based on a transparent evaluation. The development of such a scheme is therefore necessary as a sub-goal. The application of transparent criteria within the evaluation scheme allows for a quantitative evaluation, which can be used for further qualitative conclusions. Only a limited choice of life cycle methods can be taken into account. The developed evaluation scheme is, however, expected to provide a basis for potential evaluation of further methods.

In addition to the theoretical evaluation of the selected life cycle methods the thesis aims to gain information from the application of case studies in order to check the theoretical findings.

The thesis will deliver justifiable insights in the suitability of the life cycle methods for different objectives as well as a basis for the analysis of further methods.

## 1.3 Outline of the Thesis

In chapter 2 a selection of life cycle based methods is introduced with regard to their general features and a qualitative overview of strengths and limitations. The method introductions rely on general descriptions of the respective methods as well as on previous studies on their advantages or disadvantages.

A comprehensive evaluation scheme is then developed in chapter 3 consisting of ten criteria covering general, methodological and technical issues of importance to the application of the life cycle methods. The criteria are described by sub-criteria, which were defined by aspects in order to ensure transparency and traceability. As part of the evaluation scheme it is also defined how the quantitative scoring is undertaken based on compliance of the methods with the considered criteria.

The developed evaluation scheme is applied to the selected life cycle methods in chapter 4 for two different levels of application on which life cycle studies are conducted: one is the application on the level of micro decision-making, which usually refers to decisions concerning a specific product. The other application is n the level of macro decision-making, which usually refers to decisions involving either a broad geographical reason or an entire industrial sector [EC 2010c].

In chapter 5 a number of case studies is conducted for two of the considered life cycle methods to establish the basis for a practical verification of the theoretically obtained results. The limitation of the case studies to two methods is necessary due to practical as well as analytical reasons as described in chapter 5.

The findings of the evaluation are discussed in chapter 6. Here the theoretical results are considered first followed by a discussion on the results from the case studies. Finally the course of the case studies' application and their results are checked against the theoretical implications.

Chapter 7 provides final conclusions from the thesis and an outlook on further necessary research.

# 2 Characterisation of the Life Cycle Methods

According to the objective of this thesis several life cycle methods are selected which are focussed on environmental issues and are (in theory) applicable to both the micro and macro level. As the environmental assertions drawn from the application of the methods are not restricted beforehand the selected life cycle methods should be designed broadly with regard to potential environmental impacts. Therefore methods, which focus only on specific environmental issues such as energy, e.g. Energy Analysis (EA), or material input, e.g. Material Input Per unit of Service (MIPS) are not evaluated in this study.

The following life cycle based methods are therefore selected:

- **Process-based Life Cycle Assessment (P-LCA):** assessment based on physical relations between activities in the supply chain, use and end-of-life of goods or services (products) to quantify the environmental impacts, as standardised in ISO 14040 and ISO 14044 [ISO 2006a, ISO 2006b].
- **Environmental Input-Output LCA (EIO-LCA):** assesses environmental effects using data for economic input-outputs across generally national boundaries combined with emission factors for sectors within these boundaries [HENDRICKSON ET AL. 2006].
- **Material flow analysis (MFA):** assesses material and substance flows across geographic boundaries and between processes [BRUNNER AND RECHBERGER 2004].
- **Hybrid LCA:** (1) combines EIO-LCA with process-based data for the use and end-of-life stages; or (2) expands process-based LCA by adding input-output data to cover the process cut-offs [SUH 2004].

P-LCA, EIO-LCA and MFA represent methods widely applied on the decision-making levels taken into account here. While MFA does not include an environmental impact assessment it can still provide valuable information for one. Hybrid LCA as a combination of P-LCA and EIO-LCA is included to evaluate the potential of such a combination.

These methods were also evaluated by REIMANN ET AL. (2010), where “Environmentally weighted material consumption” was additionally taken into account [EURCOM 2001, REIMANN ET AL. 2010]. This method was excluded from the present thesis as it was found to provide no further input except being a means to add LCA based environmental impact assessment to MFA.

All life cycle methods under study are briefly described in this chapter. The description follows the same structure for all methods: first their basic methodological properties are described, followed by their main strengths and limitations and lastly an overview over recent developments, including developments that are currently ongoing.

## 2.1 Process-based LCA

Process-based Life Cycle Assessment (P-LCA) is a relative approach based on two international standards, ISO 14040 and ISO 14044 [ISO 2006a, ISO 2006b]. It uses physical process-based data to model product systems (including services) in order to understand their potential environmental impacts. The assessment is carried out for a specific amount of the product required to fulfil a quantified performance, represented by the functional unit. The generated process model includes all relevant data of the product's life from raw material acquisition through production, use, end-of-life treatment, recycling to final disposal within the system boundary defined for the assessment. The result of a process-based LCA can be single or multi score. However, for studies intended to be used for a comparative assertion intended to be disclosed to the public results shall not be aggregated to a single score results as such are based on value choices [ISO 2006b].

Process-based LCA requires compliance with certain principles, as listed below:

- Consideration of the entire life cycle of a product
- Focus on the environmental aspects and impacts of a product system
- Usage of an iterative approach
- Transparency and comprehensiveness
- Priority of a scientific approach, preferably based on natural science [ISO 2006a]

The basic stages of a process-based LCA are goal and scope definition, inventory analysis, impact assessment and interpretation, all of which may be conducted iteratively as illustrated in Figure 1.

The goal needs to be specified very clearly and should address the intended use and user group of the study. The scope is highly dependent on the goal and therefore on the intended use as well. According to [ISO 2006a] it should include, among others, the product system, its boundaries and its functional unit, assumptions and methodological decisions as well as data requirements and the choice of impact categories.

The inventory stage comprises of data collection and calculation of all relevant input and output energy and material flows of the system in question.

The impact assessment stage uses the data collected for the inventory and uses it to evaluate potential environmental impacts caused by the inputs and outputs. The impact assessment comprises mandatory and optional elements. Within the mandatory part the inventory results are assigned to different impact categories and the category results are calculated. There is no definite set of impact categories, which have to be considered for the impact assessment in process-based LCA. There is, however, guidance within the standards as to how impact categories should be selected: Impact categories shall take into account and be consistent with the goal and scope of the study and they shall be environmentally relevant with regard to the product system [ISO 2006b]. In order to facilitate interpretation the optional elements intend to condense and aggregate data by normalizing, grouping or weighting it.

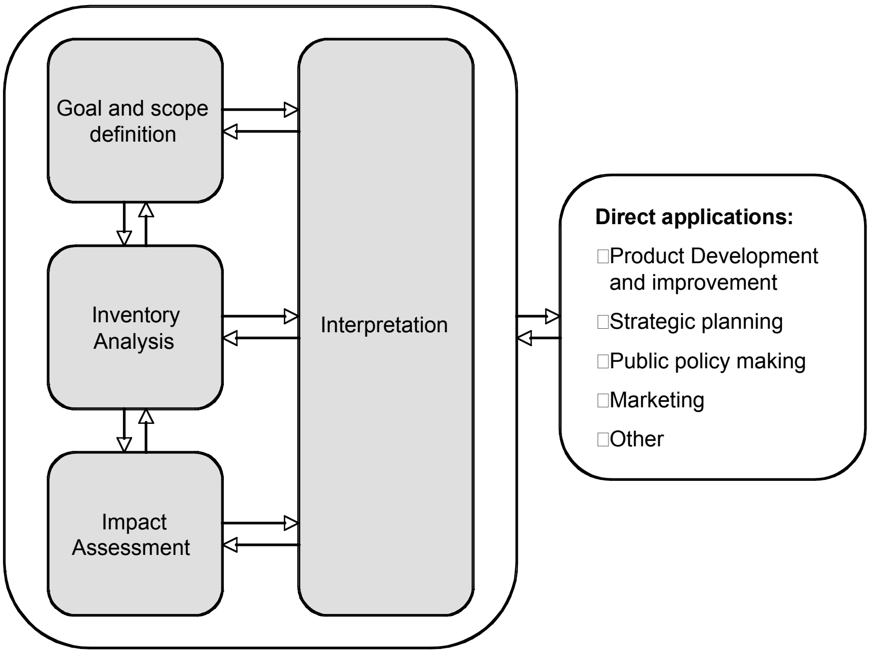


**Figure 1: Stages of a process- based LCA [ISO 2006a]**

During the interpretation phase the findings of the inventory and the impact assessment are both considered to draw goal-consistent conclusions and arrive at recommendations.

For a more detailed introduction to the method see GUINÉE (2002), KLÖPFFER AND GRAHL (2009) and the set of documents provided by the International Reference Life Cycle Data (ILCD) handbook [EC 2010a, EC 2010b, EC 2010c, EC 2010d, EC 2010e, GUINÉE 2002, KLÖPFFER AND GRAHL 2009].

Data as required by P-LCA can be found in commercial and non-commercial databases (see [EC 2008, ECOINVENT CENTRE, GaBi, PROBAS]), but can also be obtained through specific measurements or from literature.

### 2.1.1 Historical development

The concept of systematic life cycle thinking in order to aggregate the impacts caused by products first arose in the late 1960s, early 1970s. In the beginning there was no distinction between inventory and impact assessment since the main interest lay in energy. Therefore discussions about the assignment of different environmental impacts were of no importance yet [BOUSTEAD 1996].

The need for an extended impact assessment became obvious with the increasing knowledge about environmental problems and relations. In the middle of the 1970s first approaches included qualitative ABC analyses, value-benefit analyses or entropy approaches. Starting from a resource-focussed perspective the assessment moved to a more general and environmental mechanism based approach [SIEGENTHALER 2006].

A milestone in the method development was the first internationally acknowledged conceptual framework on LCA, published by the Society of Environmental Toxicology and Chemistry (SETAC) in 1993 [SETAC 1993].

Another important step towards the process-based LCA, as it is used today, was the beginning of the standardisation, which began in November 1993, leading to the publication of the ISO standards 14040 to 14043 between 1997 and 2000. These standards built the foundation for consistent application and comprehension of the method [MARSMANN 2000].

### 2.1.2 Current developments

Interest in LCA is reflected by wide range of initiatives and societies concerned with methodological as well as data improvements. Exemplarily the UNEP-SETAC Life Cycle Initiative and the European Platform on LCA shall be mentioned on a trans-national level [EC 2008, LC INITIATIVE]. The UNEP/SETAC Life Cycle Initiative aims at continuous overall improvement of the different life cycle methods, with an emphasis on information and dissemination issues, though methodological issues are approached as well. The European Platform on LCA aims at significant improvement of consistency and quality across P-LCA data, methodological issues and studies through the implementation of the International Reference Life Cycle Data System (ILCD).

On a national level there are for example the Brazilian LCA Network, the Japanese AIST - Research Institute for Safety and Sustainability, the Nordic Life Cycle Association or German Network Life Cycle Data [AIST, BACV, ITAS-ZTS, NorLCA]. Apart from aiming at providing country specific LCA data these national projects often target capacity and awareness building and general provision of life cycle related information.

The P-LCA standards have been revised and published in 2006 to incorporate new developments [FINKBEINER ET AL. 2006]. The revision aimed at enhancing the readability and delete mistakes and inconsistencies.

In general current research is concerned with a number of issues. For the impact assessment there are still environmental issues not or not adequately addressed by research, e.g. local categories such as noise and odour or the wide area of land use. Data quality and uncertainty in LCA are problems, which are still not completely solved [FINKBEINER ET AL. 2006, ISO 2006a, ISO 2006b]. Consequential LCA, which takes into account the consequences to the material and energy flows caused by changes in the life cycle, or the introduction of time into LCI modelling are still under development [ZAMAGNI ET AL. 2008]. Concerning data work continues on the databases in order to advance a widespread application of LCA.

### 2.1.3 Major applications

P-LCA has been applied in many different decision making situations. On one hand its uses include strategic statements on a political or scientific level regarding the environmental performance of whole product groups. On the other hand P-LCA has been widely used on a corporate level in order to compare specific products. Branches applying P-LCA range from the plastic industry or steel industry to agriculture as well as the building or textile industry; basically there is no limit to the range of branches P-LCA can be applied to. Applications included both: assessments of existing products and their environmental impact and assessments of the environmental outcome of future changes.

The user group is composed of all societal parties such as policy makers, agencies, research institutes and companies. Some studies carried out by governments had a large influence on national policy making, for example the German study on beverages packaging by the Federal Environment Agency [PLINKE ET AL. 2000]. Industry associations such as the European Aluminium Association (EAA), the Association of Plastics Manufacturers PlasticsEurope or the International Iron and Steel Institute (IISI) have been active in the field of LCA for a long time and have been providing data on their respective branches.

### 2.1.4 Strengths

P-LCA is a method, which can be adapted flexibly and used for a wide range of application, on a strategic as well as an operational level both for comparisons and optimisations. The stringent life cycle approach avoids a shifting of problems.

It provides quantitative information on the system in question and directly relates physical information of the system to potential environmental impacts in a transparent way. The method also allows for the relation of different sites [GUINÉE 2002].

### 2.1.5 Limitations

The intended coverage of the whole life cycle is often not possible in practice, so cut-offs are necessary which may contribute to an underestimation of the related environmental impacts. Other assumptions such as allocation procedures have an impact on the result as well, but are not regulated in detail (though the now available ILCD handbook gives more specific instruction [EC 2010c]).

As far as the impact assessment is concerned there are also methodological uncertainties as there is not one universally accepted consistent approach; this in particular affects the weighting. The missing relation to time and location may distort the result compared to the actual situation.

Data collection for a P-LCA can be time and cost consuming since all processes need to be modelled. Regional differences are often not reflected by the data. Since existing data was usually collected for developed countries there is a lack of specific data for developing countries. Furthermore there may be difficulties involved due to proprietorship and confidentiality.

## 2.2 Environmental Input-Output LCA

Environmental Input-Output LCA (EIO-LCA) represents an economy-wide assessment, which includes direct and indirect environmental effects, i.e. effects caused by the industry sector itself and its suppliers as well as wider effects in the economy caused by the suppliers' suppliers. It generally relies on publicly available statistical data and therefore leads to reproducible results [HENDRICKSON ET AL. 2006].

Economic input-output (IO) tables are utilized to map interdependencies between sectors in the economy of a given region and quantify those relationships in monetary terms. For EIO-LCA environmental factors are assigned to sectors if the IO tables.

The total economic effect generates environmental emissions across the economy. The IO table is linked with emission factors to calculate the total emissions associated with an economic demand (e.g., EUR 1 demand for electricity). The emission factors are calculated by dividing the total annual emissions from each sector in an IO table by the total annual output of this sector. The resulting emission factor (in units of emissions/EUR) is then multiplied by the output from the sector [HENDRICKSON ET AL. 2006].

Considered impact categories are not defined for EIO-LCA but various impacts can be included in the calculation.

The method requires regionally defined (often national) economic IO tables which differ in their provision. Within the European Union for instance, input-output tables are required every five years and Supply and Use tables (SUT) every year by the ESA-95 regulation [EUR COUNCIL 1996]. The latter can be used as the basis for IO tables under certain assumptions. These tables are standardized and give data on 60 sectors and product groups with a required maximum lag of three years. The voluntary system National Accounting Matrix including Environmental Accounts (NAMEAs) uses the same sector differentiation to provide data for several emissions to air [TUKKER ET AL. 2009].

### 2.2.1 Historical development

Wassily Leontief won the Nobel Prize in economics for the I-O methodology in 1973, and he also explored the possibility to use it for environmental assessment [LEONTIEF 1986]. But it was researchers in Japan (at various institutes like NIES and AIST) and the U.S. (Carnegie Mellon University's Green Design Institute) that developed the I-O-based model.

An early example of the EIO-LCA approach is Joshi's Ph.D. dissertation [JOSHI 1998] that documents the need for a combined use of EIO-LCA and process LCA. His journal paper [JOSHI 2000] applies the method to the comparison of a steel and a plastic fuel tank of a Chevrolet van. The analysis uses the detail of the process analysis to define precisely the gas tank to be considered, then uses EIO data to trace out the economy-wide implications of buying the desired quantity of each material. While mainly EIO data was used in the analysis, some resource inputs and environmental emissions in the use and end-of-life phase, as well as in steel tank welding, were estimated using process data. Other examples of early application of this approach included a study of a midsize passenger car [MACLEAN AND LAVE 1998] that used process data for the use stage and EIO data for every other stage (but ignored end-of-life treatment), and [LAVE ET AL. 2000] that extended the automobile inventory analysis to diesel and compressed natural gas.

### 2.2.2 Current developments

One current methodological issue is the sector disaggregation (see chapter 2.4 for description) as part of the Hybrid LCA, another one the issue of the treatment of imported goods. This is starting to be addressed by the introduction of multi-region input-output (MRIO) models. WIEDMANN ET AL. (2007) distinguish between linked single-region models and true multi-region models [WIEDMANN ET AL. 2007]. The first type accounts for the last stage of the international chain only, while the latter type combine domestic production with coefficients from multiple countries or regions. An overview of recently developed MRIO models is given by WIEDMANN (2009), the majority of which incorporate environmental information on greenhouse gases [WIEDMANN 2009]. An important recent development in this is the database of the "Global Trade Analysis Project (GTAP7), which was launched in December 2008 and covers 113 regions with 57 sectors [GTAP 2008].

Developments in EIO-LCA often concern data provision as seen within the EXIOPOL project, which aims at estimating external costs of major environmental impacts of EU 27 and including these external costs in a comprehensive environmentally extended input-output table covering approximately 130 sectors and products [EXIOPOL 2007, TUKKER ET AL. 2009]. The World Input-Output Database (WIOD) project will further contribute to harmonized national IO tables. In particular, the tables in the WIOD-database will provide data for the 27 EU countries and 13 other major countries covering more than 30 industries and at least 60 products [WIOD 2009].

EUROSTAT has recently tendered a series of six projects, which aim at establishing an environmentally-extended multi-regional input-output system for Europe, see [EUROSTAT 2009]. The specific objectives of these six projects include comprehensive data collection in the areas of monetary and physical modules of Eurostat's Environmental Accounts and the development of processing routines for the implementation of IO-LCA.

### 2.2.3 Major applications

EIO-LCA has been applied to a number of products, goods and services, including examples from the following industries: construction, automobile, energy, transportation, electronics, information technology. A list is found in reference [HENDRICKSON ET AL. 2006].

For the European level the study on "Environmental Impact of Products (EIPRO)" constitutes a major application of EIO-LCA [TUKKER ET AL. 2006a]. The project delivered life cycle information on products, which have the greatest environmental impact within EU-25.

User groups include the Green Design Institute at Carnegie Mellon University (Pittsburgh, Pennsylvania, USA), various research institutes and groups in Japan (e.g., NIES, AIST), the research groups around Arpad Horvath at the University of California, Berkeley, Sangwon Suh at University of Minnesota, Heather MacLean at the University of Toronto (Canada) and Chris Hendrickson and H. Scott Matthews at Carnegie Mellon University (Pittsburgh, Pennsylvania, US) as well as the PE Consulting Group (Echterdingen, Germany).

### 2.2.4 Strengths

The main strength of EIO-LCA lies in the economy-wide coverage, thus making cut-offs unnecessary. It can be used to calculate the overall impact of a sector or product group and also gives information on indirect flows which are not always apparent. It provides a consistent framework for the allocation of environmental impacts for a defined region. Relying on data already aggregated it avoids extrapolation of data on specific products when studying product groups rather than individual products.

### 2.2.5 Limitations

Input-Output models do not generally cover the whole life cycle as information on use and waste management phases is not included [TUKKER ET AL. 2006b]. For the use and disposal phase a different data source is therefore needed which means that data from different sources must be employed if these life cycle stages are to be covered.

The assumption of proportionality between economic flows and environmental impacts is not verified.

The method generally assumes the same production technology for imported goods as for domestic ones and also homogeneity within product groups bundled up to sectors [SCHEPELMANN ET AL. 2009]. Therefore over- or underestimations may occur for imported goods.

According to TUKKER et al. (2009) the resolution in the IO tables would need to be higher to be able to distinguish between important sectors. Moreover, impacts can only sufficiently be analyzed for greenhouse gases and – to a lesser extent – emission related to acidification [TUKKER ET AL. 2009]. Therefore the level of detail may not be sufficient for an intended life cycle study even though many countries now provide IO tables.

## 2.3 Material Flow Analysis

Material Flow Analysis (MFA) is used to characterise the flows and stocks within a defined regional or technological system based on physical inputs and outputs. Many different approaches are subsumed under the term of MFA, two of which are introduced here: Substance Flow Analysis (SFA) is chosen as representative for micro level applications of MFA and Economy-wide MFA (EW-MFA) for applications on the macro level which were also included in the CALCAS project as methods relating to life cycle based analyses [JESWANI ET AL. 2008].

The term Substance Flow Analysis (SFA) refers to a type of MFA, which is concerned with substances such as copper and zinc. Furthermore, it is an important tool for identifying sources of hazardous substances that may potentially be released to the environment. SFA can be used to assess how a set of substances is managed with respect to resource availability and environmental impact. The method provides quantified physical information about stocks and flows of a substance in a certain time period and for a specific region. It can also reveal imbalances over time [BRUNNER AND RECHBERGER 2004, SCHEPELMANN ET AL. 2008 ].

EW-MFA on the other hand is concerned with nationwide material flows and provides an aggregated overview of the annual physical inputs and outputs of an economy including imports and exports and flows to and from the environment, see Figure 2. Only flows across the functional border are considered, the economy itself is treated as a black box. EW-MFA are compiled on the input side by using data on domestic extraction and imports as well as indirect flows which are connected to imports, e.g. the up-stream indirect flows of unused extraction. On the output side emissions and waste are calculated, along with the dissipative use of products and losses, the disposal of unused domestic extraction and exports as well as the indirect flows associated to exports. In addition the net difference in stock is calculated. [EURCOM 2001] By balancing the physical flows of a country EW-MFA is a satellite account to the System of National Accounts. It is harmonized on a European as well as international level; see [OECD 2008, WEISZ 2007].

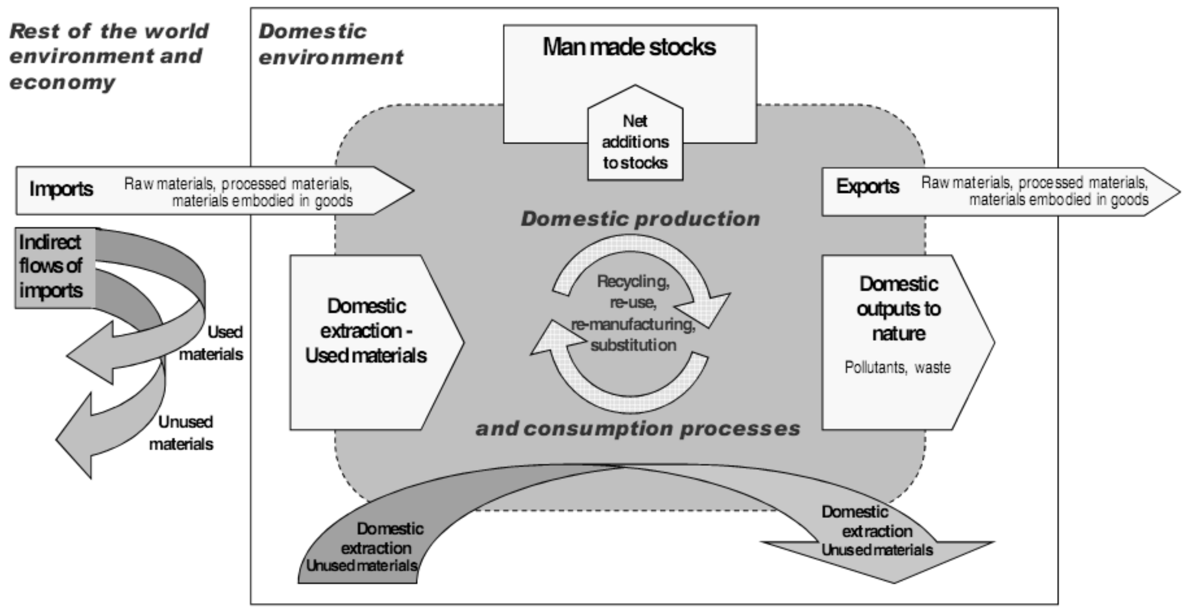


**Figure 2: Schematic representation of an economy-wide material balance scheme [OECD 2008]**

The database is usually formed by statistics on physical inputs and outputs.

### 2.3.1 Historical development

SPATARI et al. reviewed the development of the history of MFA/SFA in their paper [SPATARI ET AL. 2002]: Much SFA work has been carried using steady-state flow models for copper and other metals at national and global scales [GORTER 1997, JASINSKI 1995, SPATARI ET AL. 2002, THOMAS AND SPIRO 1994]. In addition, many SFA case studies are published by Conaccount, a research exchange organized by the Wuppertal Institute ([BRINGEZU ET AL. 1997, KLEIJN ET AL. 1998]). These studies have examined systems of substance flows over short periods, such as one year, and emphasize the flow of substances rather than stock accumulation in different reservoirs.

Regional MFAs have been conducted for decades and by now EW-MFA is harmonized on a European as well as international level, see [OECD 2008, WEISZ 2007].

### 2.3.2 Current developments

Developments in the field of MFA is highly connected with data provision as there is still a need to obtain MFA/SFA data to cover most elements and regions. MFA/SFA is now extensively conducted by Yale University, University of Tokyo, Tohoku University, NTNU etc. The regions in the focus are now becoming more widely spread. The Stocks and Flows Project (STAF) conducted by Yale University evaluates stocks and flows of significant materials throughout the world for different time spans [CHRISTENSEN ET AL. 2007]. Focussing on metal cycles it aims at combining their stocks and flow findings with environmental considerations. In addition the resulting models are publicly accessible and will be used for the prediction of development scenarios.

**Table 1: MFA/SFA case studies focusing on EU and individual member states**

| Author(s) | Element/ Material | Region | Reference |
|---|---|---|---|
| Spatari et al. | Cu | EU | [SPATARI ET AL. 2002] |
| Graedel et al. | Cu | Germany, EU, World wide | [GRAEDEL ET AL. 2004] |
| Gorter J. | Zn | The Netherlands | [GORTER 1997] |
| Johnson et al. | Ag | France, Germany, EU, World wide | [JOHNSON ET AL. 2005] |
| Johnson et al. | Cr | EU, World wide | [JOHNSON ET AL. 2006] |
| Elshkaki et al. | Pb | EU | [ELSHKAKI ET AL. 2005] |
| Melo M. T. | Al | Germany | [MELO 1999] |
| Kleijn et al. | PVC | Sweden | [KLEIJN ET AL. 2000] |

On the macro level the data basis is improving with the harmonisation of MFA data as done by the OECD guide but also by the provision of individual national data sets. The OECD council recommendation on resource productivity which was adopted in 2008 is likely to further facilitate EW-MFA applications as member countries are encouraged by it to improve their analysis of material flows and related environmental impacts. An online portal from the

Sustainable Europe Research Institute (SERI) was launched, providing MFA data on a national level [SERI]. For the US there is a pilot MFA database available, see [WRI 2005].

The approaches to MFA described above comprise static modelling methods. There are, however, also efforts to incorporate dynamic models, see for example [BINDER ET AL. 2001, KLEIJN ET AL. 2000, ZELTNER ET AL. 1999]. These models apply past production and consumption figures along with in-use residence times and project these to future situations. Such a model would therefore be appropriate for scenario analyses, though it requires additional data and modelling skills [SCHEPELMANN ET AL. 2008]. Table 1 shows MFA/SFA case studies focusing on EU and individual member states.

### 2.3.3 Major applications

All MFA approaches serve as tools to understand the functioning of the physical basis of societies, the inter-linkages of processes and product chains, and the exchange of materials and energy with the environment [MOLL ET AL. 2003].

Depending on the focus of the study two basic strategies can be distinguished: dematerialization and detoxification [BRINGEZU AND MORIGUCHI 2002]. Detoxification refers in this context to the reduction of emission of hazardous substances to the environment. Dematerialization means the increase in resource efficiency, i.e. the decoupling of material consumption and economic growth.

The two major application fields of MFA were regional metabolism analysis and regional analysis of pollutant pathways. Additional evolving applications include process control, waste management and resource conservation and recovery. The method can be used on various spatial systems such as towns, regions, countries as well as on a global level and it can be applied on e.g. economy sectors or households [BRUNNER AND RECHBERGER 2004]].

A major application of EW-MFA is its utilization as a satellite to the System of National Accounts.

### 2.3.4 Strengths

SFA is a relatively simple tool to provide an overview of all flows of a specific substance within the system boundary, which allows for the identification of the source of environmental issues. Both SFA and EW-MFA can be used to estimate future generation of waste or emissions and they give a comprehensive and consistent balance account of their respective object of study. The approaches can account for direct as well as indirect flows and case of EW-MFA imports and exports are accounted for.

### 2.3.5 Limitations

As the method only gives information on pressure indicators, but does not comprise an impact assessment, the decision support is unclear. This is particularly relevant when considering different types of flows, such as unused extractions and further processed materials, for which the environmental relevance can differ highly.

For SFA there is an inherent danger of problem shifting if only one substance or a limited number of substances is taken into account.

When time series are needed the data availability issues become increasingly difficult. Data for EW-MFA is available for various – particularly developed – countries, but often not exhaustive [SCHEPELMANN ET AL. 2008]. For developing countries the availability of data is usually quite limited for MFA/SFA studies.

## 2.4 Hybrid LCA

Hybrid approaches combine the scope of the economy-wide EIO-LCA model with the detail of process analysis. While process models improve and extend the possibilities for analysis, EIO-LCA simplifies the modelling effort and avoids errors arising from the necessary truncation or boundary definition for the network of process models. For the most comprehensive analysis, the best features of both approaches should be employed.

Hybrid LCA basically links process-based LCA and EIO-LCA by applying two approaches: either the input-output table is improved by including process-based data for important flows, or the process-based analysis is expanded by adding input-output data [SUH AND NAKAMURA 2007].

*Tiered hybrid analysis* uses a full process-based product system, which is connected with an input-output table at the upstream and downstream cut-offs (boundaries of analysis). The combination of both approaches is not clearly defined and can be accomplished flexibly. In some cases, most of the analysis can be done using process-based data, and only basic modules, for which there are typically no or less reliable process-based data, are assessed with EIO-LCA. In other cases, EIO-LCA analysis enters the process tree at a high level of the input chain, for example, at the direct input stage, and is used for a substantial part of the life-cycle analysis. This is the case, for example, when the analysis includes service industries as EIO-LCA is typically a good source of service sector economic and environmental data, while process-based data for services are difficult to find.

*Integrated hybrid LCA* on the other hand disaggregates the information given in the input-output tables, and uses process-based data for a more specific and more useful EIO-LCA analysis. For example, the EIO-LCA sector „iron and steel mills“ includes many different iron and steel products (e.g., rails or steel sheets), thus the current use of this EIO-LCA sector in environmental assessment is limited because the environmental data are expressed as an „average iron and steel product“. However, if this sector is disaggregated into, e.g., „rails“ and „other iron and steel mill products“, and economic data for these two products are entered in the cells of the two separate columns, „rails“ becomes a distinct steel product that can be further analyzed environmentally.

### 2.4.1 Historical development

The hybrid LCA approach has been developed as a collaborative project between Horvath (University of California, Berkeley, USA), Florin (PE Consulting Group, Germany) and Matthews (Carnegie Mellon University, USA). Their methods have been described in Chapter 2 of reference [HENDRICKSON ET AL. 2006].

PACCA AND HORVATH (2002) have published the first hybrid LCA study of electricity generation by analyzing the construction (with EIO-LCA) and the use (with process-based data) of electric power plants, including hydropower, coal, natural gas, solar, and wind [PACCA AND HORVATH 2002].

### 2.4.2 Current developments

The popularity of Hybrid LCA has grown. Some Hybrid LCA studies have been done recently for complex products (e.g., buildings) and included a large number of inputs. For example, JUNNILA ET AL. (2006) have analyzed two typical office buildings in Finland and the U.S. through an application of Hybrid LCA: for the U.S. building most of the manufacturing inventories were completed using EIO-LCA and the other life-cycle phases were done using process-based LCA [JUNNILA ET AL. 2006]. CANTONO ET AL. (2008) use a hybrid approach to analyse the environmental consequenced of the introduction of fuel cell buses for transport services within the European Union [CANTONO ET AL. 2008.]

HEIJUNGS ET AL. (2006) describe the methodology for hybrid models further and provide indications on the requirements necessary for the development of a software tool for Hybrid LCA [HEIJUNGS ET AL. 2006].

Improvements in data bases include the EXIOPOL project mentioned in 2.2.2 [EXIOPOL 2007] and a Waste Input-Output (WIO) model, which constitutes an integrated hybrid model and shows a possibility for closing the gap of the end-of-life phase that is usually missing in IO tables [NAKAMURA AND KONDO 2009].

### 2.4.3 Major applications of Hybrid LCA

According to the literature review, the hybrid LCA approach has not yet been applied in practice.

### 2.4.4 Strengths

The main strength of Hybrid LCA approaches is that they can ideally combine the strengths of P-LCA and EIO-LCA and account for the respectively missing data, thus giving a more comprehensive picture than the basic methods. The approaches are flexible in the way P-LCA and EIO-LCA are combined and can therefore easily be adapted case-specific.

### 2.4.5 Limitations

The mentioned flexibility is also a limitation of the approach as two projects using EIO-LCA in substituting for process data to a varying degree (e.g. for comprehensiveness in manufacturing or service sector assessment) may yield very different results as long as there is no formal methodology.

In order to combine the two basic methods, the monetary information used for EIO-LCA needs to be linked to the physical information used by P-LCA. In general, there is lack of data for both, process-based LCA as well as EIO-LCA, but not necessarily to the same extent. This becomes a problem when doing a hybrid LCA study as one model may have more available, more specific, and better quality data available for a study than the other. For an environmental inventory of an automobile for instance, the use phase data are typically available for a specific car model and year of production, and with low uncertainty in their quality, while the available manufacturing data may not be specific to a car model, and the end-of-life data may come from one or a handful of studies and may not at all be representative for recycling or disposal conditions in a geographic area.

## 2.5 Summary

The present chapter provides an introduction to the life cycle methods considered for evaluation in this thesis. It outlines their basic approach, intent and development and highlights general strengths and limitations. It also points to more comprehensive descriptions of the methods if such information is sought. Thereby it forms a basis for the following evaluation, though it should be noted that additional information may be taken into account if necessary for detailed evaluation.

The following chapter will explain how the evaluation scheme was developed and describe in detail all considered criteria as well as defining aspects.

# 3 Development of the Evaluation Scheme

The applicability and appropriateness of the life cycle methods shall be determined for the different levels of decision making. The current chapter therefore describes the development of such a scheme and provides comprehensive information the aspects to be considered for the evaluation given in chapter 4.

## 3.1 Previous studies

Several studies have given comparative information on P-LCA, EIO-LCA, Hybrid LCA and SFA/MFA before. These studies followed different approaches and were performed with different underlying objectives.

The CALCAS project highlighted characteristics of (among others) all the methods considered here except P-LCA in an analysis of strengths, weaknesses, opportunities and threats (SWOT) with regard to their suitability in broadening P-LCA [SCHEPELMANN ET AL. 2008, SCHEPELMANN ET AL. 2009]. BEST ET AL. (2008) aimed to assess the Ecological Footprint (EF) with regard to its applicability for measuring resource-specific impacts on the macro level [BEST ET AL. 2008]. The authors additionally analysed several methods which might complement EF studies; among these were EW-MFA and SFA. Life Cycle Assessment was considered in a pre-selection level without distinguishing between P-LCA and EIO-LCA though based on the method description it can be reasoned that the focus was on P-LCA. P-LCA was excluded from the further evaluation on the basis that it focuses on single products, not on a national level as intended in the study. The methods were evaluated through the RACER framework as laid down by the European Commission [EC 2009b] applying a quantitative scoring system. MINX ET AL. (2007) aimed to assess relevant existing methods, which could serve as a basis for the calculation of Greenhouse Gas (GHG) Emissions of products and services [MINX ET AL. 2007]. The authors included P-LCA, EIO-LCA and Hybrid LCA and applied a SWOT analysis to estimate the methods' suitability for the given task.

While all these studies provide valuable insight into the considered methods and their conclusions are taken into account for the present thesis, none of them provide a comprehensive evaluation as is the aim of this study. These previous studies are focussing on qualitative information as used for SWOT analyses and/or narrow in their approach, thereby excluding several relevant and widely applied methods. Therefore they cannot provide the comprehensive and detailed analysis of life cycle based methods covering broadly designed scopes as is the aim of this thesis.

## 3.2 Approach of this thesis

The present study aims to provide a comprehensive comparative evaluation of selected life cycle based methods. The SWOT approaches applied in the CALCAS project and by MINX ET AL. (2007), as mentioned above, provide information not detailed enough for this purpose. The quantitative RACER approach applied by BEST ET AL. (2008) is more suitable as it provides a very detailed evaluation of a variety of different aspects of the considered methods due to the focus on a set of specific criteria. Thereby it enables a comparison of not only an overall suitability but also of specific traits of the methods. However, criteria taken into account must be chosen with regard to their significance for the purpose of this thesis.

To ensure balanced and defensible conclusions the development of a transparent and comprehensible evaluation scheme is necessary for which a comprehensive set of criteria is introduced. The criteria used here originate from the EVALCA project where they were chosen as being relevant and comprehensive for the study [REIMANN ET AL. 2010]. As the EVALCA project forms a basis of the thesis, the criteria are adopted with some modifications here. They follow the RACER framework laid down by the European Commission. RACER stands for relevant, accepted, credible, easy to monitor and robust against manipulation [EC 2009b].

The criteria are grouped into three different categories and broken down into ten criteria. Each criterion is defined by a number of sub-criteria. The evaluation will be done on the level of criteria, but scores will be assigned on the level of sub-criteria. To make the scoring more traceable each sub-criterion is described by aspects as visualized in Figure 3. The fulfilment with these aspects will be evaluated for each method and thereby their compliance with the (sub-) criteria assessed. In order to be able to differentiate more clearly without introducing a scale that is too diverse and therefore arguable scores are given for each criterion on a three-step scale:

0: No compliance
1: Partial compliance
2: Full compliance

As the assignment of quantitative scores in the framework of the evaluation is not free from subjective elements, however detailed the criteria are defined and described, leading experts in the field of the individual methods were invited to discuss the evaluation scheme itself as well as critical assessments later on, thereby ensuring a balanced and unbiased evaluation. Prof. Dr. Matthias Finkbeiner of Technische Universität Berlin provided expertise on P-LCA, Prof. Dr. Arpad Horvath of University of California, Berkeley on EIO-LCA and Hybrid LCA and Prof. Dr. Yasunari Matsuno of University of Tokyo on MFA.

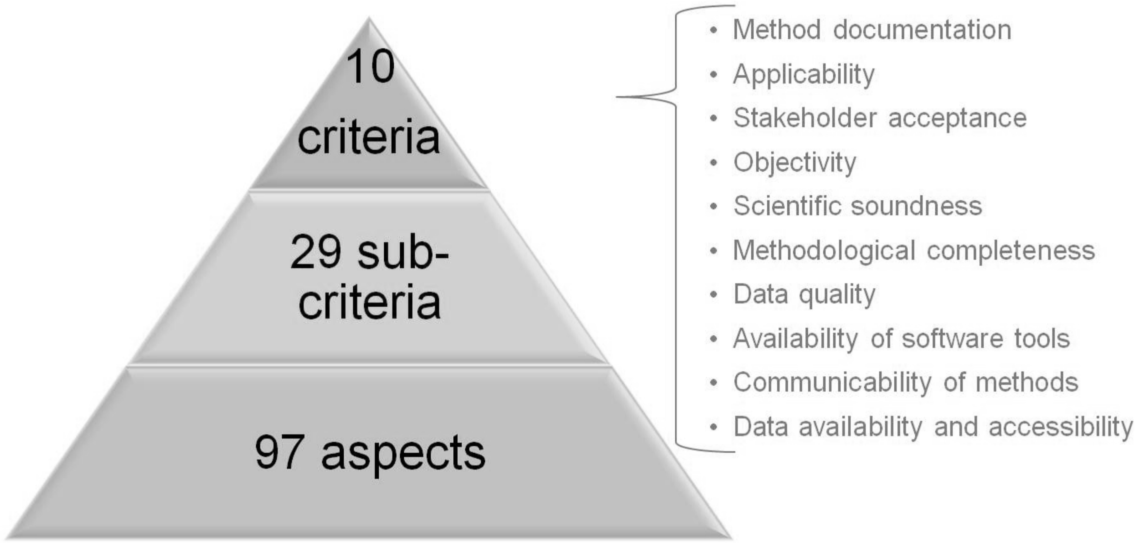


**Figure 3: Overview of criteria, number of sub-criteria and aspects**

## 3.3 Category of General Criteria

General criteria partly cover criteria important to any sound evaluation. They are independent of the assessed issue and need to be oriented to the specific study. General criteria also cover criteria considering more the perception of the respective method than its detailed properties. This category comprises of the criteria:

- Method documentation, see 3.3.1
- Applicability, see 3.3.2
- Stakeholder acceptance, see 3.3.3 and
- Objectivity, see 3.3.4

### 3.3.1 Method documentation

Documentation considered within this criterion includes the availability of guidelines and detailed expert documentation as two important sources of information but also the availability of standardisation. There is focus on how unanimous and comprehensive a set of instructions for conducting the life cycle method is. Table 2 shows the considered sub-criteria and their defining aspects.

**Table 2: Sub-criteria for method documentation and transparency**

| Sub-criteria | Considered aspects |
|---|---|
| Availability of guidelines or code of conduct | • Documents are published and accessible<br>• Documents are widely accepted<br>• Commitments to apply them on different scope levels exist |
| Detailed expert documentation | • Detailed and comprehensive description of the method exists (e.g. a textbook)<br>• Documentation is published and accessible<br>• Documentation is comprehensible<br>• Review has taken place, the source is reliable |
| Availability of standardisation for method | Level of standardisation is evaluated:<br>• in preparation<br>• in progress<br>• national standards<br>• international standardisation available |

### 3.3.2 Applicability

For the purpose of the general evaluation in this study the life cycle methods should preferably be applicable broadly as there is no specific task defined. The sub-criteria describing applicability are therefore concerned with the range of goods and services and the range of tasks that can – theoretically – be addressed. The criteria are expected to be important in distinguishing between the different scope situations. However, it shall be noted that in different circumstances a narrowly specialized method may have advantages. Table 3 shows the considered sub-criteria and their defining aspects.

**Table 3: Criteria for applicability**

| Sub-criteria | Considered aspects |
|---|---|
| Broad range of goods and services | Method is applicable for a broad range of goods and services, with as few exceptions as possible:<br>• All stage of the value chain should be considered (consumer goods, intermediate goods, etc)<br>• Both, goods and services can be assessed<br>• Method is flexible to adjustments in the system definition (depending on goal and scope of the study) |
| Broad range of tasks | Possible tasks include<br>• Comparison of systems<br>• Marketing and communication (e.g. for eco-labelling, |

| Sub-criteria | Considered aspects |
|---|---|
| | political campaigns for greener products)<br>• Detailed assessment of changes<br>• Identification of drivers and tracers<br>• Identification of cause-effect chains<br>• Improvement analyses<br>• Deduction of potential changes |

### 3.3.3 Stakeholder acceptance

The degree of acceptance of the method by the stakeholder is accounted for through two issues: the inclusion of stakeholders in different processes connected with the methods and the application by different stakeholders. For the latter industry and policy makers are taken into account here. These two stakeholders are chosen as they play important roles in the considered micro and macro level applications. Research as another important stakeholder group for the application of the methods is not essential for the evaluation since in a scientific context all methods are applied in any case. These sub-criteria are connected to the ones chosen to measure the applicability of the method but the focus is different. The applicability sub-criteria place emphasis on potential applications while the criteria for stakeholder acceptance aim to measure the actual current application. Table 4 shows the considered sub-criteria and their defining aspects.

**Table 4: Sub-criteria for stakeholder acceptance**

| Sub-criteria | Considered aspects |
|---|---|
| Inclusion of stakeholders | • Included during development<br>• Included during decision-making progress (also through reviews)<br>• Stakeholder groups and their interests are treated without bias |
| Method application by industry | • Level of utilization by companies and industry sectors<br>• Voluntary commitments to apply method exist |
| Method application by policy makers | • Level of policy decision (e.g. international, national, regional)<br>• Types and numbers of policies issued<br>• Number of countries applying method on a political level |

### 3.3.4 Objectivity

Objectivity is a measure for the independence of the result regarding the user and its reproducibility. It should also give evidence on the independence of the result regarding the variation of influences such as assumptions. Reproducibility and influence of assumptions are therefore defined as sub-criteria for this topic; their defining aspects are shown in Table 5.

**Table 5: Sub-criteria for objectivity**

| Sub-criteria | Considered aspects |
|---|---|
| Reproducibility | • Results do not depend on user applying the method<br>• No restrictions occur with regard to the user group<br>• Results do not change with repeated application<br>• Results do not change due to variations in geographical or temporal scale<br>• Results are distinct |
| Influence of assumptions | • Extent of value choices as part of the method is low (regarding method implicit assumptions on data, their aggregation, non-scientific based relations)<br>• Necessary value choices are clearly stated<br>• Possibility of uncertainty analyses and quantification of influence of assumptions |

## 3.4 Category of Methodological criteria

The methodological criteria are evaluated in order to assess the completeness and correctness of the life cycle methods. They concern the question if the methods' principles and procedures are appropriately defined. The criteria in this category are:

- Scientific soundness, see 3.4.1
- Methodological completeness, see 3.4.2 and
- Data quality, see 3.4.3

### 3.4.1 Scientific soundness

Scientific soundness is an important criterion in order to achieve dependability and balance of the result. For this study more general aspects of scientific soundness such as validity and reliability will not be taken into account since they are not measurable directly here. Rather these issues will be evaluated indirectly through the inclusion of validation or verification checks and the plausibility of the results obtained by a method as defined in Table 6.

**Table 6: Sub-criteria on scientific soundness**

| Sub-criteria | Considered aspects |
|---|---|
| Validation/ verification checks | • Errors are recognisable<br>• Checks for sensitivity, consistency, errors, etc. are mandatory (not all of these have to be included)<br>• Possibility of disaggregation of results against environmental measurements<br>• Critical and peer (with lesser significance) reviews are mandatory for key parts of method/results |
| • Plausibility of results | • Direct measurement of environmental effects<br>• Scientific correlation between used data and environmental assessment<br>• Strong link between used data and results<br>• Collection and processing of data is consistent with intention of result |

### 3.4.2 Methodological completeness

Methodological completeness is achieved if procedures regarding all important aspects of the method exist. It is therefore evaluated if the method is defined for system boundaries and multifunctional situations. Though there are more procedural definitions necessary for the application of the methods, these are essential for all studied life cycle methods while others may only be applicable for certain methods. Furthermore, under the objective of this study a method should be suitable for a comprehensive environmental assessment and enable the analysis of the whole life cycle. Table 7 shows the considered sub-criteria and their defining aspects.

**Table 7: Sub-criteria on methodological completeness**

| Sub-criteria | Considered aspects |
|---|---|
| Method defined for system boundary | • Procedure for setting the physical boundaries (which stages, processes and flows are to be included)<br>• Definition of cut-off criteria |
| Method defined for multifunctional situations | • Possible ways for dealing with the topic are described<br>• Priorities are set, with favour to scientific procedure |
| Method suitable for comprehensive environmental assessment | • The means to display differentiated & comprehensive picture of impact situation, covering natural resources, human health and ecosystem quality |

| Sub-criteria | Considered aspects |
|---|---|
| | • Consideration of double counting<br>• Procedures for impact assessment defined, incl. selection and modelling of categories<br>• Appropriateness for studied question<br>• Environmental impact is correctly reflected (no distortion/influence by other factors, as e.g. monetary ones) |
| Method enables analysis of whole life cycle | Method targets all major life cycle phases:<br>• Resource extraction<br>• Production<br>• Use<br>• End-of-life, including recycling, reuse, disposal |

### 3.4.3 Data quality

The actual data quality is dependent on a specific case study. However, there are aspects and procedures which can be evaluated on a methodological level in order to estimate how well a method will be able to ensure high data quality. Therefore characteristics of data commonly used for the life cycle methods are evaluated, as is their representativeness. In addition it is taken into account if there are procedures in existence for the documentation of data and if data is commonly reviewed. Table 8 shows the considered sub-criteria and their defining aspects.

**Table 8: Sub-criteria on data quality**

| Sub-criteria | Considered aspects |
|---|---|
| Data characteristics | • Independence of economic and environmental information<br>• Originally intended level of resolution (micro or macro level) is consistent with level of application<br>• Minimal time lag between data collection and data provision |
| Data representativeness | Data is able to characterise system appropriately in terms of<br>• Time span (also considering data updates)<br>• Technology coverage<br>• Geographical coverage<br>• Type of measurement |
| Independent review | • Internal reviews or<br>• External/Third party reviews<br>• Review procedures are defined |

| Sub-criteria | Considered aspects |
|---|---|
| Data documentation | • Documentation should be transparent<br><br>Documentation should occur regarding<br>• Data characteristics<br>• Representativeness aspects<br>• Review procedures |

## 3.5 Category of Technical criteria

The technical criteria encompass issues related to the feasibility of applying the methods. These criteria provide an indication of the manageability and effort involved with the method application. The following criteria are considered within this category:

- Availability of software tools, see 3.5.1
- Communicability of the method, see 3.5.2 and
- Data availability and accessibility, see 0

### 3.5.1 Availability of software tools

Availability of software plays an important role for feasibility as it facilitates the handling of systems which in the case life cycle considerations are usually complex. They can also help to structure and communicate results. In order to ensure objectivity and scientific soundness it is beneficial if different tools could be employed. The sub-criteria considered here therefore concern the number of available tools but also the variation in license models to ensure high accessibility, see Table 9.

**Table 9: Sub-criteria on the availability of software tools**

| Sub-criteria | Considered aspects |
|---|---|
| Number of available tools | • Existence of simplified tools (permitting conduction of entire study but having very limited adaptation options)<br>• Existence of expert tools (characterised by high level of adaptation options, e.g. in choice of assessment method and changeability of parameters for sensitivity analysis or similar) |
| Variation in licence models | • Free licenses (increasing access for different user groups)<br>• Commercial licences (enhancing the quality of supply through competition and long term support/development) |

### 3.5.2 Communicability of method

The communicability of the methods is enhanced if the method is clear and the basic structure simple, which will therefore be evaluated. The same is true if the calculation of results is comprehensible and transparent. It could be argued that this last sub-criterion could – with a slightly different focus – also be part of other criteria, e.g. scientific soundness, but in order to avoid double-counting it will only be evaluated here. Furthermore communicability is influenced by the level of awareness regarding a method. It will therefore be evaluated if established tools for communication exist for a method. This takes into account actual existence of tools, contrary to the criterion for broad applicability, which considers the potential of the life cycle method to serve as a basis for communication tools. Table 10 shows the considered sub-criteria and their defining aspects.

**Table 10: Sub-criteria on communicability**

| Sub-criteria | Considered aspects |
|---|---|
| Clarity of method | • Simplicity of basic concept, also for non-experts<br>• Relation between steps of method are comprehensible, connections logical and transparent<br>• Unambiguousness of result |
| Comprehensible calculation and transparency | • Basic data is accessible for review<br>• Calculation is documented in detail<br>• Functional model, e.g. dependencies and relations are apparent |
| Established communication | • Existence of tools for communication (e.g. EPDs)<br>• Previous communication examples exist, which can be consulted for support<br>• Level/goal/success of previous communication examples<br>• Adaptability to cover different target audiences |

### 3.5.3 Data availability and accessibility

The criteria for availability and accessibility of data are combined into one topic since both are influenced by the same aspects. Evaluated are the issues if data covers the whole life cycle, if it is available for different regions but also for relevant impact categories and there are inventory databases, which can be accessed freely or at an affordable cost. The sub-criteria and their aspects are shown in Table 11.

**Table 11: Sub-criteria on data availability and accessibility**

| Sub-criteria | Considered aspects |
|---|---|
| Availability of data for the whole life cycle | Data covers<br>• Material extraction<br>• Processing<br>• Use phase<br>• Recycling/disposal etc. |
| Availability of inventory data for different regions | • Data available for different continents/industrial & trade areas (covering different state-of-the-arts or emission factors)<br>• Data adaptable to region-related evaluations |
| Availability of inventory data for all relevant impact categories | Data covers<br>• Global warming<br>• Acidification<br>• Human toxicity<br>• Ozone layer depletion<br>• Eutrophication |
| Publicly accessible inventory databases at affordable cost | Variety of databases exist, covering<br>• Free databases<br>• Non-profit databases<br>• Commercial databases |

## 3.6 Summary of the developed evaluation scheme

The present chapter provides detailed information on the developed evaluation scheme, structuring the criteria which are to be considered and filling them with sub-criteria and describing aspects. The development of this evaluation scheme constitutes the accomplishment of an important sub-goal of this study as it provides the basis for a comprehensive quantitative and subsequently also qualitative evaluation, as it has not been carried out before. The scheme may furthermore be applied to other life cycle methods, which are beyond the scope of this thesis but for which a similar evaluation of their suitability may be desirable.

By keeping in mind previous studies undertaken to evaluate and compare different life cycle methods, as introduced in 3.1, the present evaluation scheme is able to add several new aspects to a valuable analysis of the methods. For one it broadens the possible application greatly and can be used for the evaluation of the methods on a general basis, with focus to both micro and macro level applications. It also enables for a partly quantitative evaluation, which can be completed by qualitative assertions and conclusions. However, the quantitative estimations based on clear and transparent aspects add a valuable component beyond a purely qualitative discussion. Experts from the fields of the respective methods were consulted in order to ensure an unbiased and balanced evaluation scheme. These experts also delivered valuable feedback on the actual evaluation, the results of which are shown in the next chapter.

# 4 Evaluation of the Life Cycle Methods on a Theoretical Basis

The evaluation encompasses two scopes: a product and process perspective on the micro level and a sector or economy-wide perspective on the macro level.

The micro perspective is typically connected to decision making related to specific products or product groups. This is applicable both in industry and policy domain. A company might want for instance to apply a life cycle method in order to improve the environmental performance of its production or the resulting product by e.g. implementing more efficient resource (including energy) consumption or a switch in the materials used [EC 2010c].

The macro perspective, on the other hand, is linked to policy questions involving a nation or a broader region like the EU-27 or an entire industry sector. For instance, the monitoring of the decoupling between economic growth and overall environmental impact of the EU-27 consumption system, as addressed in the Thematic Strategy (TS) on resources, is an important case where a life cycle approach is required [EC 2010c].

The quantitative evaluation is done on the level of the sub-criteria for reasons of transparency; the results will be discussed in a more comprehensive matter on the criteria level.

## 4.1 General criteria

For the category of general criteria the methods' compliance with the following criteria is evaluated:

- Method documentation, see 4.1.1
- Applicability, see 4.1.2
- Stakeholder acceptance, see 4.1.3 and
- Objectivity, see 4.1.4

In each of these chapters the compliance with the criteria is evaluated by dividing them into sub-criteria and taking into account aspects as described in 3.3. An overview of the results in this category is shown for the criteria level in 4.1.5.

### 4.1.1 Method documentation

The criterion on method documentation comprises of the following sub-criteria:

- Availability of guidelines or code of conduct, see 4.1.1.1
- Detailed expert documentation, see 4.1.1.2 and
- Availability of standardization, see 4.1.1.3

The evaluation of each considered method against the aspects describing these sub-criteria is given in the following paragraphs, along with the resulting quantitative scores. An overview of all quantitative results for the compliance with the criterion is shown in 4.1.1.4.

#### 4.1.1.1 Availability of guidelines or code of conduct

##### Evaluation for P-LCA

Guidelines can be found on both the micro and the macro level. They exist for single product, several industries and also on a public policy level. The first to be published were the SETAC guidelines, which is widely accepted as a basis for micro level applications [SETAC 1993]. More recently the ILCD handbook provided extensive guidelines for both the micro and the macro level [EC 2010a, EC 2010b, EC 2010c, EC 2010d, EC 2010e]. Examples of macro level sectoral guidelines are one for the steel industry, for the paper industry or guidelines by the plastics industry regarding groups of polymers, which urge their members to apply these [FEFCO 2006, PlasticsEurope 2009, WSA 2002]. The criterion is therefore rated as fulfilled on both levels. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 12.

##### Evaluation for EIO-LCA

There are no guidelines or codes of conduct specifically for EIO-LCA on the micro level. However, for the macro level guidelines can be found for the separated part of economic and environmental accounting as well as guidelines integrating both of these accounting parts, which are accepted and applied for the regions they apply to [EC 2008, UN 2003]. The criterion is rated as not fulfilled on the micro level and completely fulfilled on the macro level.

##### Evaluation for MFA

For MFA no specific guidelines or similar exist for the application on the micro level. On the macro level there is a methodological guide for economy-wide material flow accounts published by the European Commission as well as one by the OECD which are accepted and applied for the regions they apply to [EURCOM 2001, OECD 2008]. The criterion is rated as not fulfilled on the micro level and completely fulfilled on the macro level.

##### Evaluation for Hybrid LCA

For Hybrid LCA the general LCA guidelines should be applied and are valid since all hybrid approaches are a combination of P-LCA and EIO-LCA. As there is currently not a practical record of applications of Hybrid LCA there are consequently no commitments to follow such guidelines. The criterion is therefore rated as partially fulfilled on both levels.

**Table 12: Quantitative evaluation for the sub-criterion on availability of guidelines**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Availability of guidelines | 2 | 2 | 0 | 2 | 0 | 2 | 1 | 1 |

#### *4.1.1.2 Detailed expert documentation*

***Evaluation for P-LCA***

Extensive and reliable expert documentation on P-LCA in the form of textbooks can be found, e.g. the Handbook on LCA by GUINÉE or the Hitch Hiker's Guide to LCA by BAUMAN AND TILLMANN, to name but two [BAUMAN AND TILLMAN 2004, GUINÉE 2002]. The peer reviewed International Journal of Life Cycle Assessment (IJLCA) is devoted entirely to LCA, though not exclusively to P-LCA but to EIO-LCA as well. In addition, the journal Environmental Science & Technology (one of the top-ranked environmental journals in the world) and the Journal of Industrial Ecology have been publishing reviewed P-LCA papers regularly. Most of these documents are traditionally concerned with micro level issues, but the journals also publish papers on macro level application. Compliance is therefore rated complete on micro level and partially fulfilled on macro level. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 13.

***Evaluation for EIO-LCA***

A complete textbook on EIO-LCA, describing the methodology and case studies is given by [HENDRICKSON ET AL. 2006]. HEIJUNGS AND SUH (2002) are also primarily concerned with the methodology of EIO-LCA [HEIJUNGS AND SUH 2002]. As mentioned above the International Journal of LCA has published work on the EIO-LCA and by now also given the method a "subject area" so reviewed documentation is accessible (and can be expected to grow) [SUH AND NAKAMURA 2007]. In addition, the Journal Environmental Science and Technology and the Journal of Industrial Ecology have been publishing EIO-LCA papers regularly. The focus of the documentation available for the EIO-LCA is focused more on the macro level, i.e. sector-wide applications than on micro or single-product applications. The compliance with the criterion is rated complete on the macro level and partially fulfilled on the micro level.

***Evaluation for MFA***

BRUNNER AND RECHBERGER (2004) published an extensive textbook on MFA [BRUNNER AND RECHBERGER 2004]. There is no journal devoted entirely to MFA but different journals publish regularly work on MFA, e.g. the Journal of Industrial Ecology and the Journal for Cleaner Production. The focus is mainly on macro level for which compliance with the criterion is rated complete, but general principles apply again for the micro level as well.

### Evaluation for Hybrid LCA

So far the method is documented mainly alongside EIO-LCA and P-LCA, but usually not exclusively. Documentation is available, but is not comprehensive and apart from the subject area within the International Journal of LCA there is no explicit detailed expert documentation yet. There is no distinguishable difference between micro and macro studies, for both levels compliance is currently not fulfilled.

**Table 13: Quantitative evaluation for the sub-criterion on detailed expert documentation**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Detailed expert documentation | 2 | 1 | 1 | 2 | 1 | 2 | 0 | 0 |

## 4.1.1.3 Availability of standardisation

### Evaluation for P-LCA

For P-LCA international standardisation is available, though it is primarily focused on micro level [ISO 2006a, ISO 2006b]. Specifications on up-scaling from micro level data to macro level topics are not available. Though the standard is theoretically valid for macro level applications as well, compliance will be partially restricted. According to the considered aspects compliance with the sub-criterion is rated complete on micro level and partially fulfilled on macro level. The quantitative scores of P-LCA and the other methods for this sub-sub-criterion are shown in Table 14.

### Evaluation for EIO-LCA

EIO-LCA uses a monetary representation of the physical flows connected with a product system. As the ISO standards 14040 and 14044 aim at modelling by using physical (material or energy) flows, there is a discrepancy [ISO 2006a, ISO 2006b]. However, EIO-LCA generally starts the LCA of a product or service with a physical notion of the problem. Thus, the current 14040 and 14044 standards apply in principle. At the moment there are no efforts to specifically standardise EIO-LCA. Compliance with the sub-criterion is rated partially fulfilled on both levels.

### *Evaluation for MFA*

There is no standardisation available for MFA at the moment.

### *Evaluation for Hybrid LCA*

The limitations found for "pure" EIO-LCA apply for the hybrid approaches as well since monetary flows are used at least partially. The degree of compliance with the international standards ISO 14040 and 14044 is therefore case dependent and is rated as partially fulfilled on both levels for the purpose of this study.

**Table 14: Quantitative evaluation for the sub-criterion on availability of standardisation**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Availability of standardisation | 2 | 1 | 1 | 1 | 0 | 0 | 1 | 1 |

### *4.1.1.4 Results of the criterion for method documentation*

The quantitative results for method documentation are shown in Figure 4. The figure reveals a complete compliance of P-LCA with the criterion on the micro level and a more than half-fulfilled compliance of P-LCA, EIO-LCA and MFA with it on the macro level. The result for MFA is particularly low on the micro level as there are neither guidelines nor standardisation.

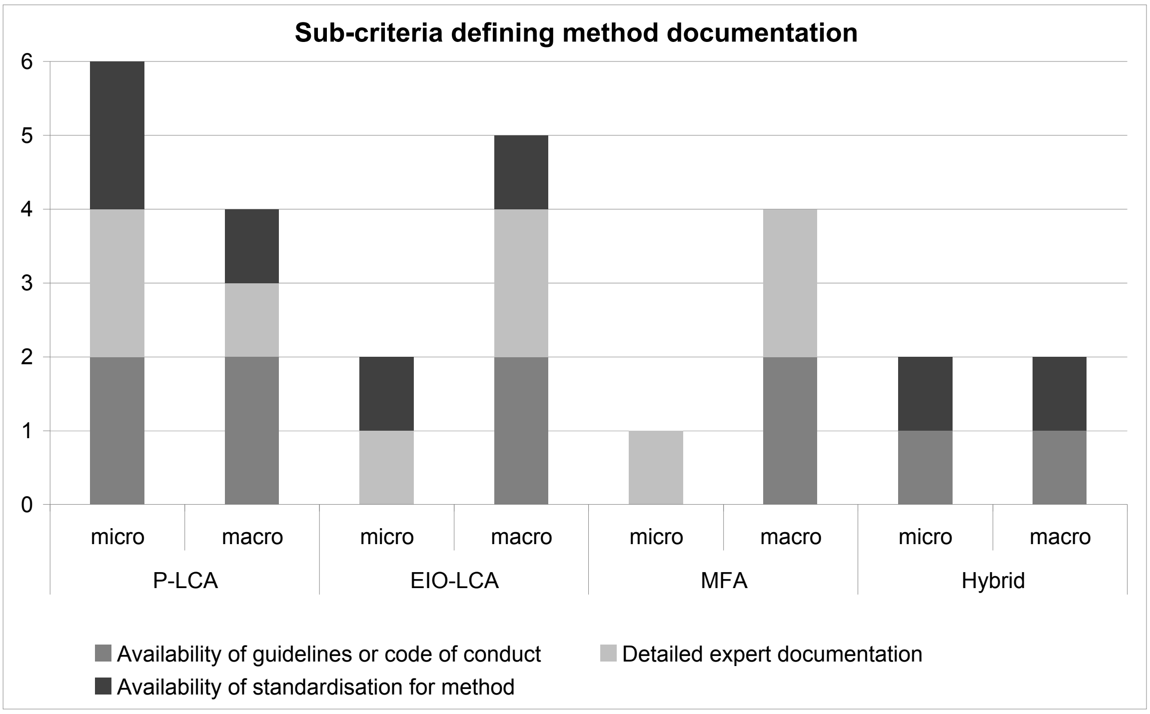


**Figure 4: Quantitative results of compliance with method documentation, divided to the sub-criteria level**

### 4.1.2 Applicability

The criterion on applicability comprises of:

- Applicability with a broad range of goods and services, see 4.1.2.1 and
- Applicability with a broad range of tasks, see 4.1.2.2

The evaluation of each method against the aspects describing these two sub-criteria is given in the following paragraphs, along with the resulting quantitative scores. An illustration of all quantitative results for the compliance with the criterion is given in 4.1.2.3.

#### *4.1.2.1 Broad range of goods and services*

***Evaluation for P-LCA***

With regard to the aspects considered P-LCA is highly compliant. The method can be used for a wide range of goods and services in all phases of the value chain. It can also be adjusted to specific requirements of a study as defined in its goal and scope. From a methodological point of view there are no restrictions on micro level. On macro level possible restrictions are due to lack of completeness in the documentation of the methods and are taken into account there. For the theoretical applicability on goods and service there is no restraint in compliance. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 15.

***Evaluation for EIO-LCA***

Due to the data basis of economic IO tables the method is applicable to all goods and services covered by the tables. It is especially valuable in assessing services which are directly included in the IO tables. The detail of IO tables, however, varies from economy to economy. However, this is not a methodological limitation but a practical one and concerns more the criterion for data availability. Flexibility differs within the method. For the part of the economic tables flexibility is low and comes rather from adaptations when the tables are updated than from requirements of a specific study. Flexibility regarding the environmental part of the method on the other hand can be assumed. Again, limitations that occur do so due to – practical – data availability, e.g. regarding included impact categories. Coverage of the value chain is not complete as IO tables only cover the pre-consumer stages. Compliance with the sub-criterion is partially fulfilled with no level-specific differences.

***Evaluation for MFA***

The focus of MFA is clearly on materials, i.e. goods, not on services. On a substance/material level applicability is not limited, but the value chain is not covered in its entirety. The system can also be adjusted according to the needs of a study, so flexibility is not an issue. The lack of application on services and the incomplete value chain coverage cause the compliance with the sub-criterion to be partially fulfilled on both micro and macro level.

### Evaluation for Hybrid LCA

Due to the combination of EIO-LCA and P-LCA flexibility and adaptability is high, as is the range to which cases the method can be applied. Both goods and services can be assessed along the whole value chain. The rating is therefore complete on both scope levels.

**Table 15: Quantitative evaluation for the sub-criterion on applicability for broad range of goods and services**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Broad range of goods and services | 2 | 2 | 1 | 1 | 1 | 1 | 2 | 2 |

## 4.1.2.2 Broad range of tasks

### Evaluation for P-LCA

The tasks defined in the evaluation scheme can be covered by P-LCA I general. Limitations occur on the macro level with regard to cause-effect chains and tracing of drivers and thereby also for the deduction of potential changes due to the necessary aggregation. Compliance is therefore complete on the micro level and partially fulfilled on the macro level. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 16.

### Evaluation for EIO-LCA

In contrast to P-LCA EIO-LCA is better adapted for tasks on the macro level, on which the tasks defined in the evaluation scheme can be carried out. Limitations rather occur on the micro level, where the level of aggregation renders a detailed assessment of change or improvement analyses of single products impossible. Compliance is rated as complete on the macro level, but partial for micro level applications.

### Evaluation for MFA

The tasks defined in the evaluation scheme are partially covered by MFA. Improvement analysis is an important application of MFA, especially through the identification and tracing of drivers. The assessment of change can be carried out with repeated application. The comparison of systems on the other hand is not intended and marketing applications or improvement analyses are not feasible. For both scope levels compliance of the method with the sub-criterion is rated partially fulfilled.

***Evaluation for Hybrid LCA***

Assuming a combination of P-LCA and EIO-LCA which applies both methods' respective advantages and thereby improves their limitations the compliance with the sub-criterion can be complete on both scope levels for EIO-LCA.

**Table 16: Quantitative evaluation for the sub-criterion on applicability for broad range of tasks**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Broad range of tasks | 2 | 1 | 1 | 2 | 1 | 1 | 2 | 2 |

### *4.1.2.3 Results of the criterion on applicability*

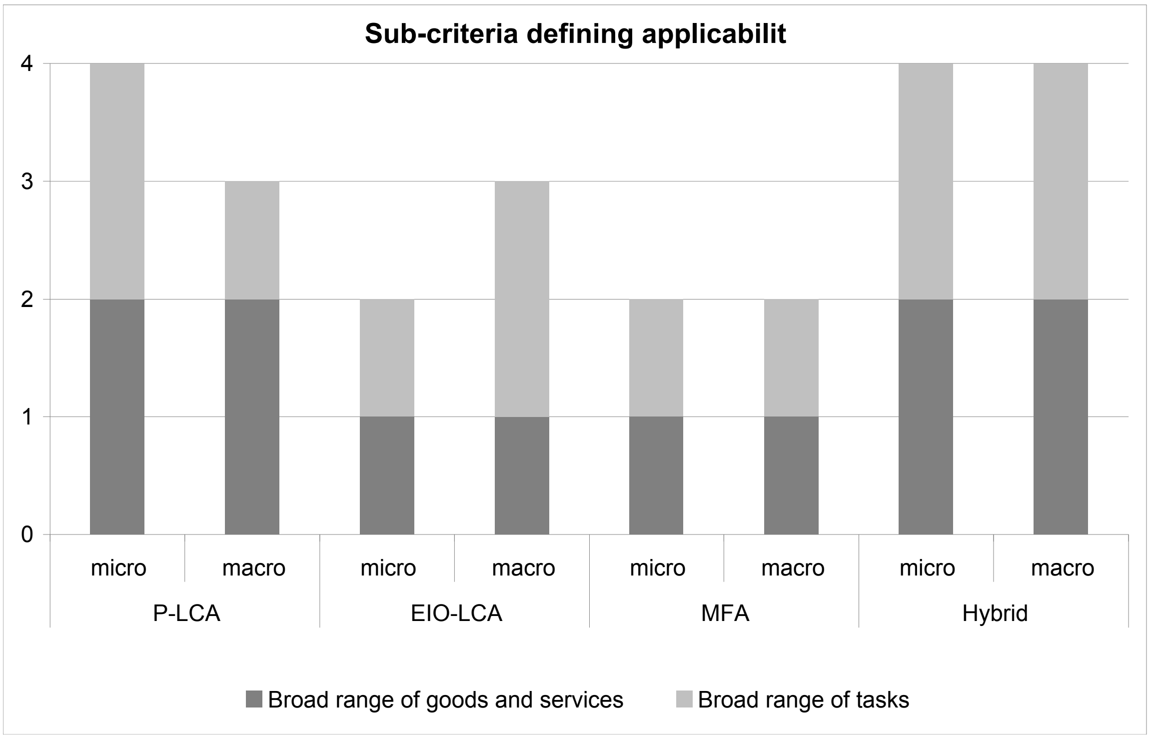


**Figure 5: Quantitative results of compliance with applicability, divided to the sub-criteria level**

Figure 5 shows the overall quantitative results of all considered methods with regard to their applicability. The figure reveals a complete compliance of P-LCA on the micro level and of Hybrid LCA on the micro as well as the macro level. However, the remaining combinations of methods and scope levels all show at least half-fulfilled compliance with the aspects taken into account for this criterion, too.

### 4.1.3 Stakeholder acceptance

The following sub-criteria are considered to evaluate stakeholder acceptance:

- Inclusion of stakeholder, see 4.1.3.1
- Method application by industry, see 4.1.3.2 and
- Method application by policy makers, see 4.1.3.3

The quantitative results for these three sub-criteria are given in the following paragraphs, an overview of the results can be found in 4.1.3.4.

#### *4.1.3.1 Inclusion of stakeholders*

##### *Evaluation for P-LCA*

P-LCA is standardised by two international standards, ISO 14040 and ISO 14044, which were developed with contributions from major stakeholder groups such as consumer, research, political and industry groups, as is procedure of the International Organization for Standardization (ISO) [ISO]. Inclusion of stakeholders during the development phase has therefore taken place. On the other hand inclusion in the decision making process is not stipulated in general, though mandatory through review process for comparative assertions. No bias in the treatment of interests can be identified. Procedures for the scaling up of P-LCA to the macro level could not be found to have included stakeholders in the development. Compliance with the sub-criterion is therefore rated partially fulfilled on both levels. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 17.

##### *Evaluation for EIO-LCA*

As the two ISO standards on LCA are in principle applicable to EIO-LCA as well, the reasoning for the method is the same as for P-LCA with regard to the inclusion of stakeholders in the development. For method development more specific to EIO-LCA there was no stakeholder engagement, nor is there any discernible for decision-making processes. Different stakeholder groups are treated without bias in general, but the distribution of sectors may lead to systematic over- or underestimation of certain industry groups. Due to these limitations compliance can be regarded as partially but not completely fulfilled.

##### *Evaluation for MFA*

For MFA no compliance can be found for the inclusion of stakeholders either in development or application of the method. Due to the focus on substances/materials the treatment of different stakeholders is not an issue implicit in the method; no bias can therefore be found. Compliance with the sub-criterion is rated as partially fulfilled on both scope levels.

### *Evaluation for Hybrid LCA*

No stakeholders were engaged in the development of Hybrid LCA though the general explanations on the ISO standards apply again. No unfair treatment or favouritism of different stakeholder groups can be discerned for the method. Overall, we rated Hybrid LCA is rated a partially compliant with the sub-criterion on both levels.

**Table 17: Quantitative evaluation for the sub-criterion on stakeholder inclusion**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Inclusion of stakeholders | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

### *4.1.3.2 Method application by industry*

### *Evaluation for P-LCA*

P-LCA is applied by industry on a regular basis for internal and external studies on the micro level, the applications conducted by industry associations are macro applications by industry. Voluntary commitments exist on the micro level for which compliance is rated complete while it is partially fulfilled on the macro level. The quantitative scores of P-LCA and the other methods for this criterion are shown in Table 18.

### *Evaluation for EIO-LCA*

Industry applications of EIO-LCA is so far not evident on either of the scope levels nor are there any commitments to do so, therefore the acceptance by industry stakeholders is rated as non-existent.

### *Evaluation for MFA*

MFA is applied for sector wide issues on the macro level but on the micro level the direct implementation of MFA in industries is limited due to the focus of the method on stocks and flows of individual substances. No commitments to apply the method could be found. No compliance can be assumed on the micro level, but partial compliance on the macro level.

### *Evaluation for Hybrid LCA*

No industry applications of Hybrid LCA is apparent at the moment, compliance is therefore rated as zero.

**Table 18: Quantitative evaluation for the sub-criterion on the application of the method by industry**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Method application by industry | 2 | 1 | 1 | 1 | 0 | 1 | 0 | 0 |

#### *4.1.3.3 Method application by policy makers*

##### *Evaluation for P-LCA*

The method has been widely applied on micro and macro level as the basis for policies. Examples for applications on the macro level include the German packaging ordinance or the European Renewable Energy Directive [BMU 2008, EC 2009a]. According to SCHENCK (2009) LCA has also widely been used as the basis for policy making in the US [SCHENCK 2009]. Compliance with the sub-criterion is rated complete on both levels. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 19.

##### *Evaluation for EIO-LCA*

There has been no known policy application on the micro level, but the method has been applied as the basis for a wide range of policy decisions and issues. For example, EIO-LCA is used in California to shape carbon footprint policy. The input-output analysis-based LCA tool CEDA has been used for policy analyses, e.g., for the Environmental Impact of Product (EIPRO) study of the European Commission and the Environmental Product Prioritization study of the Danish Environmental Protection Agency [TUKKER ET AL. 2006a, WEIDEMA ET AL. 2006]. No compliance is therefore found on the micro level, but complete compliance on the macro level.

##### *Evaluation for MFA*

There have been no policy application on the micro level, but the method has been applied as the basis for a wide range of policy decisions and issues. For example, the Japanese Ministry of Environment has conducted MFA in a national scale for many years, i.e. total inputs and outputs to and from Japan in a year. The results of MFA were used to promote 3Rs (reduce, reuse, recycling) and find some directions for waste management, with which they have introduced legislations. No compliance is found on the micro level, but complete compliance on the macro level.

### *Evaluation for Hybrid LCA*

There is currently no application by policy makers.

**Table 19: Quantitative evaluation for the sub-criterion on the application of the method by policy makers**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Method application by policy makers | 2 | 2 | 0 | 2 | 0 | 2 | 0 | 0 |

### *4.1.3.4 Results of the criterion on stakeholder acceptance*

The results of the evaluation with regard to stakeholder acceptance are shown in Figure 6. For this criterion none of the considered methods reaches full compliance, though compliance is more than half-fulfilled for P-LCA on both scope levels and for EIO-LCA and MFA on the macro level. The remaining combinations of methods and scopes only show partial compliance in one of the sub-criteria, namely the inclusion of stakeholders, as the methods have not been applied on these cases.

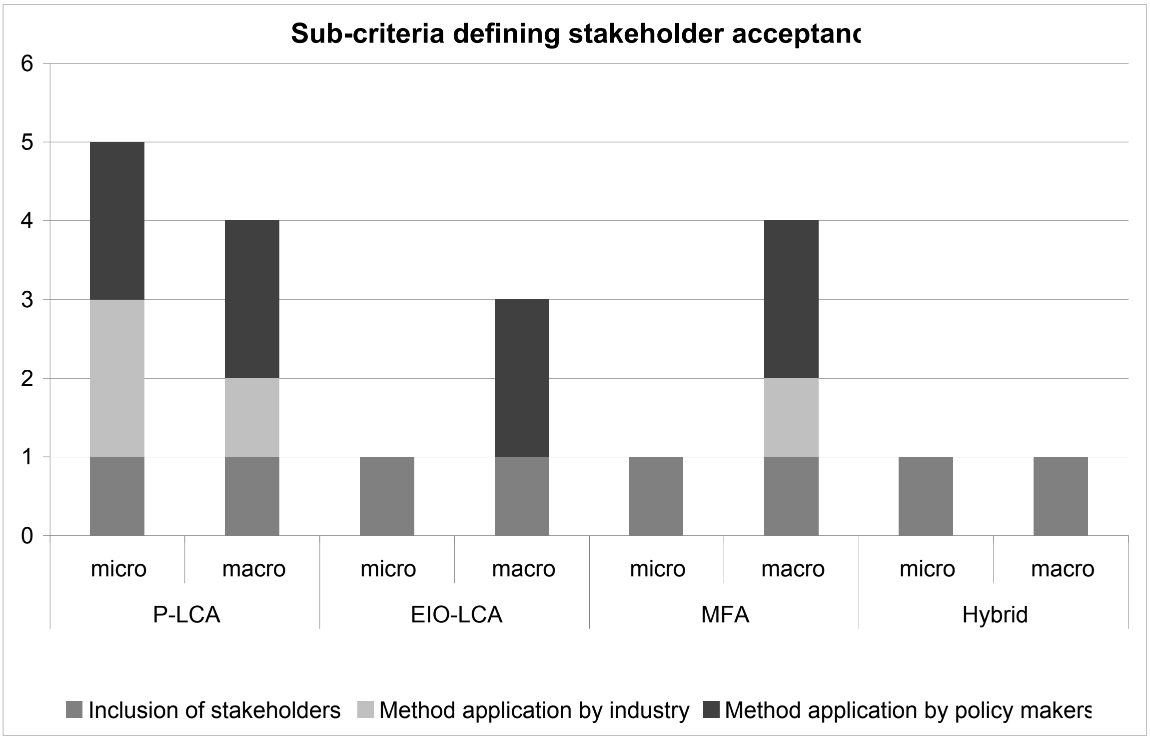


**Figure 6: Quantitative results of compliance with stakeholder acceptance, divided to the sub-criteria level**

### 4.1.4 Objectivity

Objectivity is evaluated through the following sub-criteria:

- Reproducibility, see 4.1.4.1, and
- Influence of assumptions, see 4.1.4.2

The evaluation of these sub-criteria is given in the respective paragraphs; an overview of the quantitative results of the criterion is found in 4.1.4.3.

#### *4.1.4.1 Reproducibility*

***Evaluation for P-LCA***

As stated above P-LCA is highly flexible and adaptable to different goals and scopes, including geographical or temporal ones, which may reduce reproducibility. If assumptions are differed the result is likely to change with repeated applications or when studies are conducted by different user groups. As long as the approach is well defined and done transparently reproducibility can be achieved but it is not certain. However, results are distinct and are reproducible under the same conditions. Restrictions due to different user groups will not occur assuming a sufficient level of expertise. Due to the above possibilities of restrictions compliance is rated as partially fulfilled. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 20.

***Evaluation for EIO-LCA***

EIO-LCA is more rigidly set than P-LCA which enhances reproducibility. Different user groups are likely to achieve the same results as are repeated applications. With the evaluated aspects the compliance of EIO-LCA with this sub-criterion is considered complete.

***Evaluation for MFA***

As with P-LCA, there are different approaches to apply the method, which reduces reproducibility, especially on the micro level. Results depend greatly on made assumptions and thereby on different user groups as well as variations in geographical and temporal scale. However, methodological possibilities for variations are few and approaches are clearly defined on the macro level by guidelines. Taking these limitations into consideration reproducibility is rated partially compliant on micro and macro level.

***Evaluation for Hybrid-LCA***

Given the uncertainties in the methodological description and the integration of P-LCA portions within the Hybrid LCA reproducibility is uncertain with respect to all considered aspects and is therefore rated zero on both scope levels.

**Table 20: Quantitative evaluation for the sub-criterion on reproducibility**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Reproducibility | 1 | 1 | 2 | 2 | 1 | 1 | 0 | 0 |

#### *4.1.4.2 Influence of assumptions*

##### *Evaluation for P-LCA*

Necessary value choices are to be clearly stated for P-LCA and uncertainty analyses can be conducted. However, the amount of necessary value choices is high and their influence difficult to quantify. For both levels the compliance with the sub-criterion is rated as only partially fulfilled. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 21.

##### *Evaluation for EIO-LCA*

The reliance on IO tables which cannot be influenced by the user applying the method causes value choices within these tables not immediately apparent. They occur, however, due to e.g. the structure of industries, but assumptions are documented. Further value choices are implicit in the environmental data (e.g., emissions factors are per dollar of total output of a sector), and cannot be changed by the user. Uncertainty analyses are possible, but the methods are not prescribed nor can the influence of the made assumptions be quantified. On the micro level the influence of assumptions will be higher as disaggregation of data assumes homogeneity within sectors. Compliance is therefore rated as partially fulfilled on the macro level and not fulfilled on the micro level.

##### *Evaluation for MFA*

Value choices are of importance mainly in the identification of the relevant flows and processes, which are to be considered but these are clearly stated. If data of different aggregation levels is used the comparability of these levels is implied. The problem of uncertainty is addressed but not necessarily quantified. However, the extent of value choices is low and easily documented; compliance for this sub-criterion is rated as complete.

##### *Evaluation for Hybrid LCA*

As a combination of P-LCA and EIO-LCA, Hybrid-LCA carries with it the inherent assumptions and value choices of the participating methods for those parts that are included, respectively. If this causes the overall influence of the assumptions to be lower or larger cannot be consistently analysed on a general basis and may be case specific. Compliance is therefore rated as partially fulfilled on both levels.

**Table 21: Quantitative evaluation for the sub-criterion on influence of assumptions**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Influence of assumptions | 1 | 1 | 0 | 1 | 2 | 2 | 1 | 1 |

#### *4.1.4.3 Results of the criterion on objectivity*

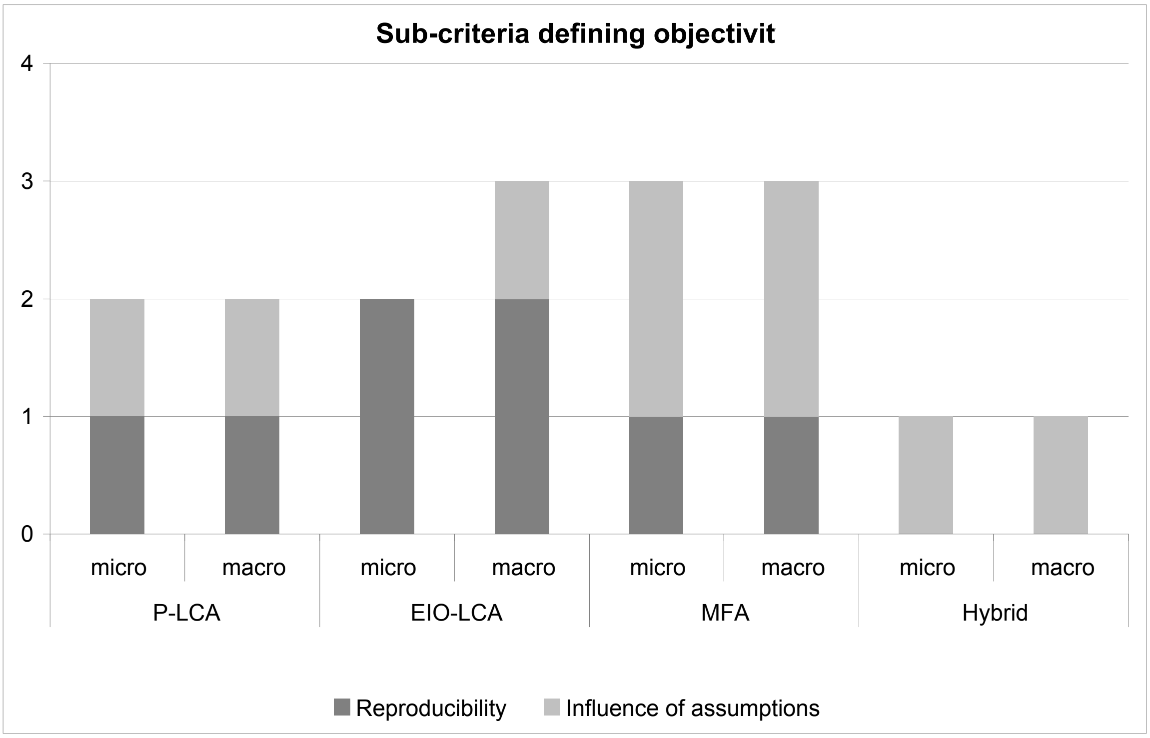


**Figure 7: Quantitative results of compliance with objectivity, divided to the sub-criteria level**

Figure 7 shows the quantitative results of the criterion on objectivity and its defining sub-criteria. It reveals that none of the considered methods show full compliance with the criterion and the aspects taken into account for this study. MFA reaches more than half-fulfilled compliance on both levels, EIO-LCA does so on the macro level. The other methods and EIO-LCA on the micro level only show half-fulfilled or lower compliance with the criterion.

### 4.1.5 Overall results of the general criteria

Figure 8 shows the merged results of the evaluation of general criteria given in the previous paragraphs. It should be kept in mind the potential highest score of method documentation and stakeholder acceptance was 6 points, for applicability and objectivity it was 4 points. On the micro level P-LCA therefore shows higher compliance with the criteria than the other considered methods. On the macro level the result is more diverse with full compliance of Hybrid LCA with regard to applicability but also high compliance (only 1 point off of complete compliance) of EIO-LCA with regard to method documentation and, of EIO-LCA and P-LCA with regard to applicability and of MFA with regard objectivity

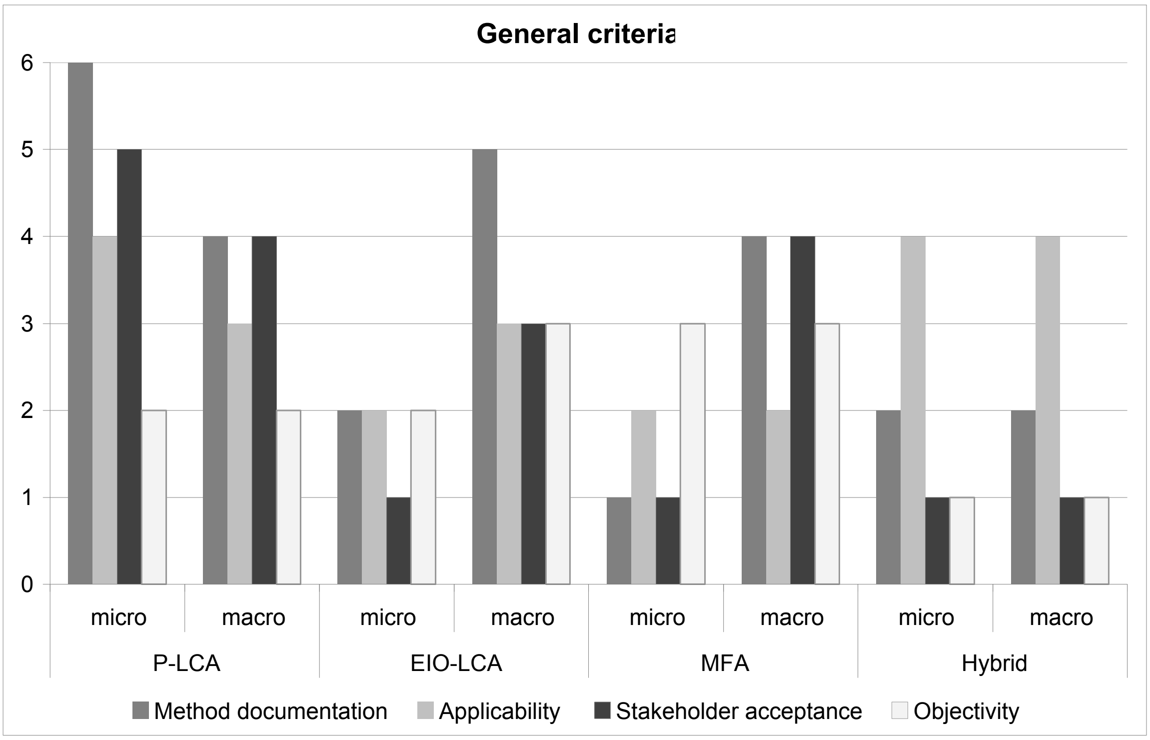


**Figure 8: Quantitative results of the general criteria**

## 4.2 Methodological criteria

Three criteria are considered to assess the completeness and correctness of the life cycle methods as is the aim of the methodological criteria:

- Scientific soundness, see 4.2.1
- Methodological completeness, see 4.2.2 and
- Data quality, see 4.2.3

The compliance of the methods with these criteria is evaluated on the sub-criteria level in the respective chapters; in addition an overview of the results on the level of the criteria is given in 4.2.4.

### 4.2.1 Scientific soundness of the approach

The following sub-criteria are evaluated to assess the methods scientific soundness:

- Validation/ verification checks, see 4.2.1.1 and
- Plausibility of results, see 4.2.1.2

The results on the criteria level are shown in 4.2.1.3.

#### 4.2.1.1 Validation/ verification checks

**Evaluation for P-LCA**

The methodology of P-LCA intends several checks on the results as well as critical reviews and peer reviews; under certain circumstances they are mandatory. Errors will therefore generally be recognizable. On the micro level results can be completely disaggregated on micro level, on macro level the possibility for disaggregation is dependent on available background information. On the micro level compliance is rated as complete, on the macro level limitations occur and compliance is partially fulfilled. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 22.

**Evaluation for EIO-LCA**

Checks and peer reviews are intended for critical parts of the method and the results. While almost all existing communication on EIO-LCA is peer reviewed, mandatory validation checks and critical reviews of all data used (not only economic IO data) are not prescribed. Disaggregation of results against economic measurements (though not against environmental measurements) is possible on macro level as the method uses macro level data to start with. On both levels compliance is rated as partially fulfilled.

**Evaluation for MFA**

Uncertainty and sensitivity checks are intended for the method. Results can be disaggregated on both levels if data collection is assumed to be done on the intended level. Critical or peer reviews are not a part of the method, but due to the clear focus on mass balances errors are easily recognisable. Compliance is rated as complete on both levels.

**Evaluation for Hybrid-LCA**

Peer reviews are intended to be completed as per the participating methods, P-LCA and EIO-LCA. So far, almost all Hybrid LCA communications has been peer reviewed, but validation checks and critical review are not mandatory. Disaggregation of results against measurements is possible as per the participating models. Compliance is rated partially fulfilled on both scope levels.

**Table 22: Quantitative evaluation for the sub-criterion on validation/ verification checks**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Validation/ verification checks | 2 | 1 | 1 | 1 | 2 | 2 | 1 | 1 |

#### *4.2.1.2 Plausibility of results*

##### *Evaluation for P-LCA*

The methodology requires a clear pathway for allocation of environmental effects to the studied system, but direct measurement of environmental effects is neither required nor usually done. On the micro level process-specific data should be used. On the macro level the potential usage of more generic data (i.e., not collected specifically for the purposes of the study) may lead to a weaker correlation between used data and results. There exists however a scientific correlation between data and environmental assessment due to the physical nature of the data. Compliance is rated complete on the micro level and partially fulfilled on the macro level. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 23.

##### *Evaluation for EIO-LCA*

On the macro level the method delivers plausible results as long as the allocation of emissions to the economy's monetary values is based on emission data covering the same economic scope as the monetary data. Direct measurement of environmental effects is neither required nor usually done. Collection and processing of data is consistent with the intention of the results on the macro level. However, the scientific correlation between monetary values and environmental assessment is disputable since monetary values depend not only on physical inputs and outputs but also on market developments. On the micro level disaggregation of macro level economic data to specific products or services may lead to less plausible results. On the micro level compliance is rated zero with regard to the considered aspects; on the macro level it is partially fulfilled.

##### *Evaluation for MFA*

The result contains quantified stocks and flows but no further condensing evaluation. Therefore results are apparent very directly and straightforwardly. In contrast to the EIO-LCA the method does not deliver results for products but for materials, which renders the disaggregation for the micro level more reliable. Results do not include a complete environmental assessment, the respective aspects are therefore not entirely appropriate here. The collection and processing of the data is nevertheless consistent with the intended result of MFA. On both levels compliance is therefore partially accomplished.

### *Evaluation for Hybrid LCA*

If the procedure for connecting EIO-LCA and P-LCA is carefully executed the plausibility of the results has the potential to be enhanced relative to the sole use of either EIO-LCA or P-LCA. Neither of the basic method measures environmental effects directly and neither does Hybrid LCA. But the scientific correlation between data and environmental assessment is improved due the integration of physical process data. On the micro level the use of P-LCA for factory-specific emissions assessment combined with the use of EIO-LCA for supply chain services assessment may enhance the plausibility of the results. On the macro level the front-end use of EIO-LCA combined with the use of P-LCA to scale up micro results for validation may enhance the results. Collection and processing of data is consistent with the intention of the results assuming an appropriate combination of the two basic methods. Compliance with plausibility is therefore rated as complete on both levels.

**Table 23: Quantitative evaluation for the sub-criterion on plausibility of results**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Plausibility of results | 2 | 1 | 0 | 1 | 1 | 1 | 2 | 2 |

### *4.2.1.3 Results on the criterion on scientific soundness*

Figure 9 shows the results for the criterion scientific soundness and reveals complete compliance with the criterion in two cases: for P-LCA on the micro level and for MFA on the macro level. However, MFA additionally reaches high compliance on the micro level for this criterion, as does Hybrid LCA on both scope levels.

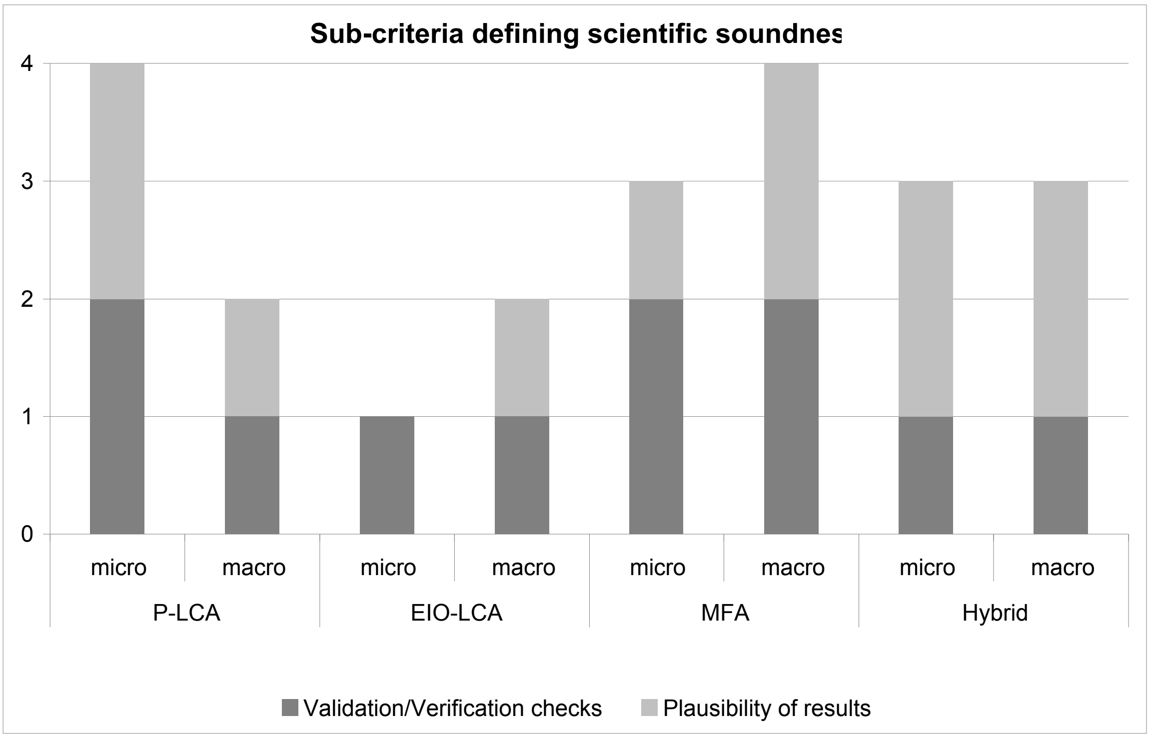


**Figure 9: Quantitative results of compliance with scientific soundness, divided to the sub-criteria level**

### 4.2.2 Methodological completeness

The sub-criteria taken into account to describe methodological completeness are the following:

- Method defined for system boundary, see 4.2.2.1
- Method defined for multifunctional situations, see 4.2.2.2
- Method is suitable for comprehensive environmental assessment, see 4.2.2.3 and
- Method enables analysis of whole life cycle, see 4.2.2.4

These paragraphs show the evaluation of each method on the sub-criteria level. An overview of the results on the criteria level is given in 4.2.3.5.

#### *4.2.2.1 Method defined for system boundary*

##### *Evaluation for P-LCA*

The system boundary of a P-LCA depends on the goal and scope of the study but there are procedures in place to set it, including recommendations on cut-off criteria. However, the specifications are not very concrete and leave a lot of room for interpretation. The requirements are focussed on micro level studies; specific demands for the macro level are not addressed. Compliance with the sub-criterion is rated as partially fulfilled on the micro level and not fulfilled on the macro level. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 24.

### *Evaluation for EIO-LCA*

For EIO-LCA system boundary are set and documented clearly. Cut-off criteria are inherently defined as they are the same as the boundary of the IO analysis. On the micro level limitations occur if the studied system does not cover the whole of the given IO table because in this case there are no specifications as to how the boundary should be set. On the macro level compliance is therefore complete, on the micro level there is no compliance.

### *Evaluation for MFA*

With MFA the issue of system boundaries is addressed and on the macro level the guidelines by EUROSTAT and OECD give a clear path as to how the system boundaries shall be set [EURCOM 2001, OECD 2008]. For the micro level no such guidelines exist. Compliance on the micro level is therefore not existent; on the macro level it is complete.

### *Evaluation for Hybrid LCA*

Procedures for setting the system boundaries are defined for the contributing methods. Assuming a greater influence of P-LCA on the micro level and of EIO-LCA on the macro level, compliance should follow the respective scoring. On micro level the aspects for the sub-criterion are therefore partially fulfilled, on the macro level compliance is rated complete as EIO-LCA defines the system boundary clearly and unambiguously.

**Table 24: Quantitative evaluation for the sub-criterion on the definition of the method for the system boundary**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Method defined for system boundary | 1 | 0 | 0 | 2 | 0 | 2 | 1 | 2 |

## *4.2.2.2 Method defined for multifunctional situations*

### *Evaluation for P-LCA*

For micro level application P-LCA fulfils both aspect of this sub-criterion due to the focus of the international standard on this level. On the macro level the standard in principle also applies, though procedures are less clear. Compliance is therefore rated complete on the micro level and partially fulfilled on the macro level. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 25.

### Evaluation for EIO-LCA

Current literature on EIO-LCA describes possible ways of dealing with multi-functional situations in EIO-LCA; see for example [RUEDACANTUCHE AND TEN RAA 2009]. These are not as generally applied and long-standing as with P-LCA so that priorities are not clearly set yet. Compliance with the sub-criterion is rated as partially fulfilled on both scope levels.

### Evaluation for MFA

The focus of the method is usually on single materials or substances thereby avoiding the issue of multifunctional situations. Since it is no issue, there are no procedures defined. But still complete compliance is assigned as no difficulties arise from this lack of procedures.

### Evaluation for Hybrid LCA

On micro level the application of the international standard is assumed for the micro level part, which sets procedures and priorities. In combination with the discussion on procedures for EIO-LCA compliance will be high. On the macro level the restrictions of both P-LCA and EIO-LCA apply. For the micro level compliance with the sub-criterion is rated complete, for the macro level as partially fulfilled.

**Table 25: Quantitative evaluation for the sub-criterion on the definition of the method for multifunctional situations**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Method defined for multifunctional situations | 2 | 1 | 1 | 1 | 2 | 2 | 2 | 1 |

### 4.2.2.3 Method suitable for comprehensive environmental assessment

### Evaluation for P-LCA

P-LCA is able to give a differentiated picture of the impact situation and also reflect the situation correctly (as far as possible based on the current knowledge). The procedures are defined and though no impact categories are preselected their choice. Double counting is addressed by the methodology. Compliance with the sub-criterion is rated complete on both scope levels. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 26.

### Evaluation for EIO-LCA

The handbook [HENDRICKSON ET AL. 2006] states that double counting is addressed, though the procedure for the impact assessment is not clearly defined. It is necessary to obtain sector-specific emissions data and some data are incomplete by default since not all companies have to report, for example, their toxic releases. Furthermore it is unclear if the environmental impacts are reflected correctly due to monetary influences cause by the IO tables. Compliance with the sub-criterion is only partially fulfilled on both scope levels.

### Evaluation for MFA

The method does not include the impact assessment itself, though it is able to deliver an objective data basis for one. For the purpose of this study, however, compliance with the sub-criterion does not exist.

### Evaluation for Hybrid LCA

Compliance with the sub-criterion is the same as the compliance of P-LCA for the process-based proportions, but limitations introduced by EIO-LCA cannot be compensated for. Thus compliance is rated as partially fulfilled on both scope levels.

**Table 26: Quantitative evaluation for the sub-criterion on the suitability of the method for a comprehensive environmental assessment**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Method suitable for comprehensive environmental assessment | 2 | 2 | 1 | 1 | 0 | 0 | 1 | 1 |

## 4.2.2.4 Method enables analysis of whole life cycle

### Evaluation for P-LCA

All life cycle stages are considered by the method, compliance is complete on both levels. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 27.

### Evaluation for EIO-LCA

With EIO-LCA, there is a focus on manufacturing, processing, and service generation, i.e., analyses located in these life cycle phases and economic sectors (industry, agriculture, mining, service sector) can be modelled. In a pure EIO-LCA no use phase and usually only very limited information on the end-of life phase is included. Compliance is only partially given for the sub-criterion.

### *Evaluation for MFA*

All life cycle stages are considered by the method through the focus on flows and stocks, compliance is complete on both levels.

### *Evaluation for Hybrid LCA*

All life cycle stages can be considered due to combination of EIO- and P-LCA. Use phase data can also be included for the IO part if certain additional information is available. Compliance is complete on both levels.

**Table 27: Quantitative evaluation for the sub-criterion on the enabling by the method to analyse the whole life cycle**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Method enables analysis of whole life cycle | 2 | 2 | 1 | 1 | 2 | 2 | 2 | 2 |

#### *4.2.2.5 Results on the criterion on methodological completeness*

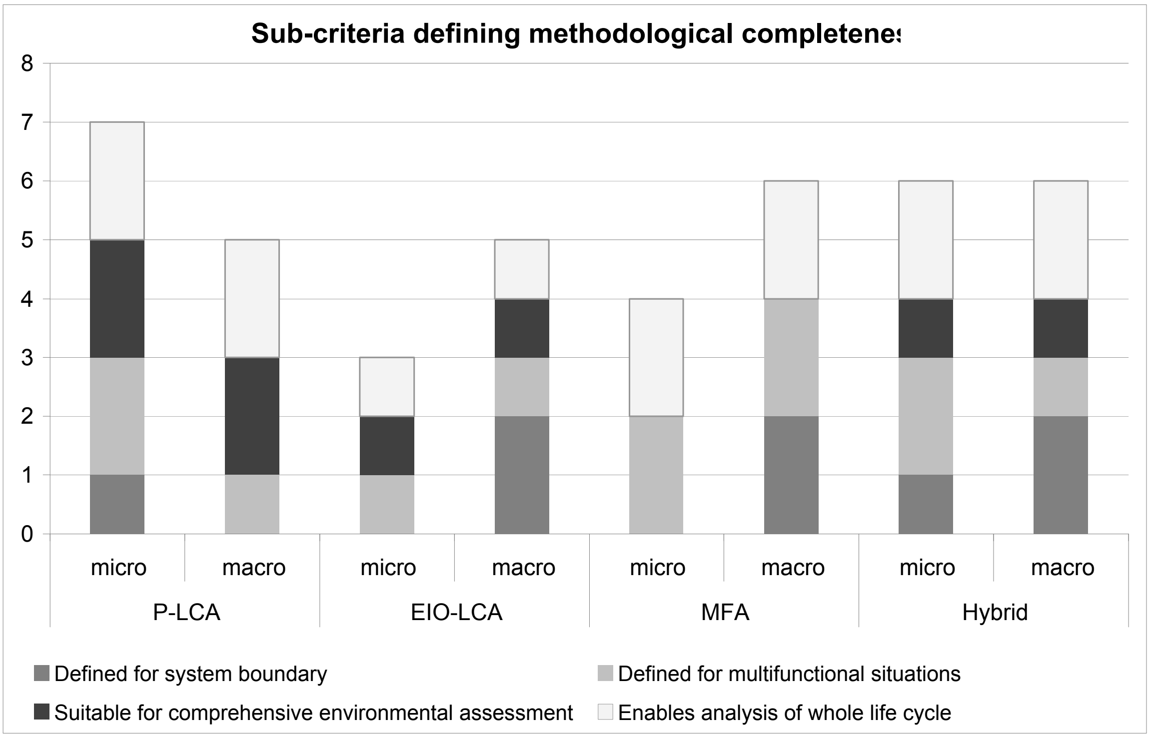


**Figure 10: Quantitative results of compliance with methodological completeness, divided to the sub-criteria level**

Figure 10 shows the quantitative results of the evaluation of all considered methods for their compliance with methodological completeness. It reveals that none of the methods achieve full compliance in this case, though P-LCA still shows the highest compliance on the micro level, MFA high compliance on the macro level and Hybrid LCA high compliance on both scope levels.

### 4.2.3 Data quality

The criterion on data quality comprises the following sub-criteria:

- Data characteristics, see 4.2.3.1
- Data representativeness, see 4.2.3.2
- Independent review, see 4.2.3.3 and
- Data documentation, see 4.2.3.4

The following paragraphs give the evaluation of all compliance of all methods with these sub-criteria and the resulting quantitative scores. The result for the whole criterion is shown paragraph 4.2.3.5.

#### *4.2.3.1 Data characteristics*

##### *Evaluation for P-LCA*

Within P-LCA environmental information is independent of economic information. Since process-based data are collected on the micro level, the originally intended level of resolution is consistent with micro level applications and the time lag between data collection and provision is minimal. For the macro level aggregation is necessary and level of resolution is not consistent, processing the data will take longer. Thus compliance on the micro level is considered complete, on the macro level there are limitations and compliance is only partially fulfilled. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 28.

##### *Evaluation for EIO-LCA*

There is a dependency between economic and environmental information, which applies to both macro and micro level. Economic data for EIO-LCA are collected on company level but aggregated and made available to the public (and thus for EIO-LCA analysis) on economic sector level. Some environmental data are collected and made available on company level (e.g., toxic emissions) while others are collected on economic sector level. Thus the level of data resolution in EIO-LCA is consistent with use on the macro level but only as a first estimate or average on micro level. There is also a significant time lag between data collection and processing and provision for the IO tables. On the micro level there is no compliance with the sub-criterion, on the macro level compliance is partially fulfilled.

### Evaluation for MFA

For MFA no dependencies between environmental and economic information occur. The data is usually collected and processed consistently with the intended study. Compliance is therefore rated as fulfilled on both scope levels.

### Evaluation for Hybrid LCA

The combination of P-LCA and EIO-LCA data leads to consistent data on both micro and macro level. However, the use of at least some EIO-LCA data leads to results where economic and environmental data are not completely independent and the limitations for a timely provision of the data exist as they do for EIO-LCA. However, the apparent limitations are expected to be minimised due to the combination and compliance is rated complete on both levels.

**Table 28: Quantitative evaluation for the sub-criterion on data characteristics**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Data characteristics | 2 | 1 | 0 | 1 | 2 | 2 | 2 | 2 |

## 4.2.3.2 Data representativeness

### Evaluation for P-LCA

Due to the functional approach the P-LCA method can achieve good data representativeness over different time spans, data sources, types of measurement and technology coverage. For macro level applications restrictions apply due to the type of measurement (as micro level data). Compliance is rated as complete on the micro level and as partially fulfilled on the macro level. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 29.

### Evaluation for EIO-LCA

On the macro level EIO-LCA can achieve representativeness regarding data sources, types of measurement and technology coverage and as the provision of IO tables becomes more common also for the time spans, though data is provided with a certain time lag. If the IO table is consistent with the studied system, representativeness is high. On the micro level technology differences are not possible to model with pure EIO-LCA and representativeness will be limited. Compliance is rated as complete on the macro level and as partially fulfilled on the micro level.

### *Evaluation for MFA*

Representativeness of MFA data can generally be assumed for the studied system on both levels and compliance is rated as complete.

### *Evaluation for Hybrid LCA*

Assuming an appropriate combination of P-LCA and EIO-LCA representativeness of used data can be assumed for the considered aspects, compliance is rated complete on both levels.

**Table 29: Quantitative evaluation for the sub-criterion on data representativeness**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Data representativeness | 2 | 1 | 1 | 2 | 1 | 2 | 2 | 2 |

### *4.2.3.3 Independent review*

### *Evaluation for P-LCA*

Internal data review is an essential part of the methodology, and third-party independent data review is part of the LCA study's peer review process. For important databases such as ecoinvent and the ELCD database review procedures are mandatory. Compliance with the sub-criterion is complete for both levels. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 30.

### *Evaluation for EIO-LCA*

For EIO-LCA internal data review is an essential part of the methodology as well as is a third-party independent data review. Cross-checks of the underlying economic data are commonly applied. Compliance with the sub-criterion is complete for both levels.

### *Evaluation for MFA*

For the macro level reviews as part of the EUROSTAT guide are essential [EURCOM 2001]. For the micro level no reviews or review procedures can be discerned. Compliance is therefore complete on the macro level and not fulfilled on the micro level.

### *Evaluation for Hybrid LCA*

Reviews are conducted as per the practices of the basic methods, EIO-LCA and P-LCA. Compliance with the sub-criterion is complete for both levels.

**Table 30: Quantitative evaluation for the sub-criterion on independent review**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Independent review | 2 | 2 | 2 | 2 | 0 | 2 | 2 | 2 |

#### 4.2.3.4 Data documentation

##### Evaluation for P-LCA

Data are required to be documented in a transparent way, both by the methodology and providers of databases. On the micro level limitations may occur due to confidentiality. Compliance with the sub-criterion is complete for the macro level and partially fulfilled for the micro level. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 31.

##### Evaluation for EIO-LCA

Data documentation is in general available for data characteristics but less so for representativeness aspects and review procedures. For both levels compliance is rated as partially fulfilled.

##### Evaluation for MFA

Data documentation is not required, but usually available and ensuring transparency for the data characteristics and representativeness aspects as well as review procedures (if existent). Compliance with the sub-criterion is complete for both levels.

##### Evaluation for Hybrid LCA

Data documentation is a necessary component of both P-LCA and EIO-LCA, therefore Hybrid LCA is expected to have good documentation as long as the contributing methods are well documented [CALCAS]. Accordingly compliance is rated as partially fulfilled on the micro level and completely fulfilled on the macro level.

**Table 31: Quantitative evaluation for the sub-criterion on data documentation**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Data documentation | 1 | 2 | 1 | 1 | 2 | 2 | 1 | 2 |

#### *4.2.3.5 Results on the criterion on data quality*

Figure 11 shows the quantitative results for the evaluation of compliance with the criterion on data quality. It reveals that both MFA and Hybrid LCA achieve full compliance with this criterion on the macro level, while none of the methods achieves it on the micro level. Compliance on the macro level is generally high as the scores of P-LCA and EIO-LCA are also high. On the micro level P-LCA and Hybrid LCA perform best, MFA also reaches a high quantitative result. EIO-LCA only achieves half of the possible score on the micro level.

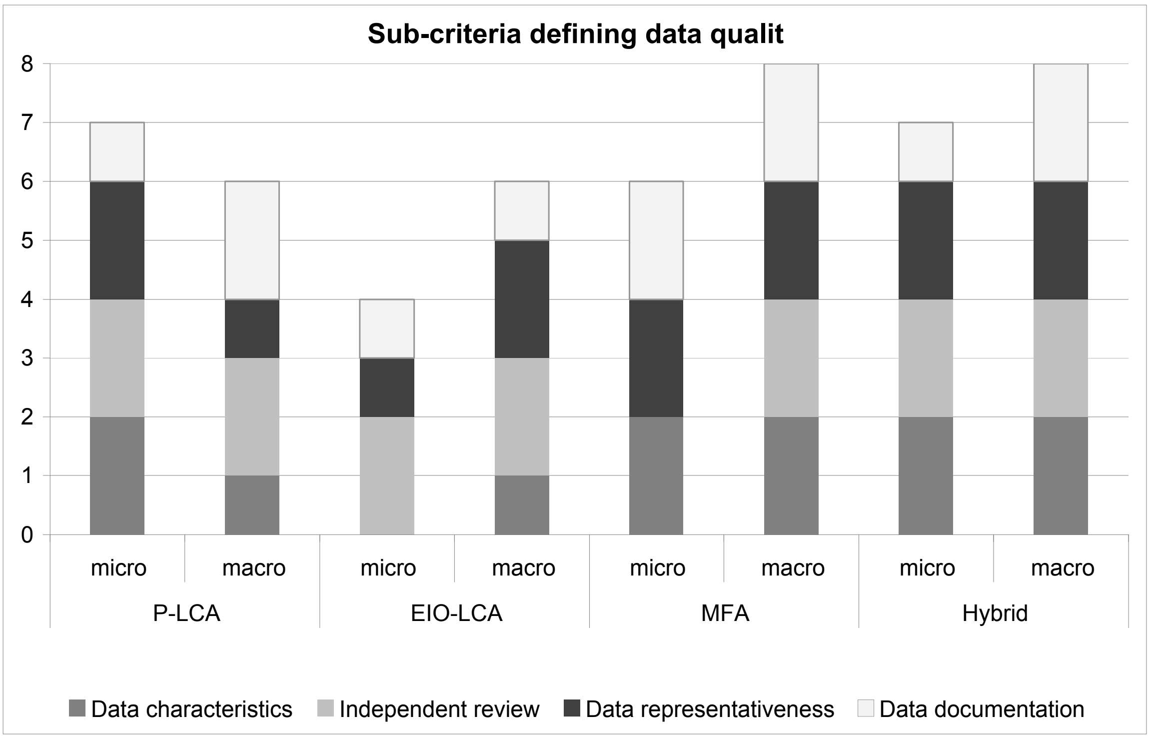


**Figure 11: Quantitative results of compliance with data quality, divided to the sub-criteria level**

### 4.2.4 Overall results of the methodological criteria

An overview of all results obtained for the methodological criteria is given in Figure 12. It should be note that as with the general criteria the possible maximum scores differed, they were 8 for methodological completeness and data quality, 4 for scientific soundness. On the micro level P-LCA achieves the highest score, though not complete for any of the criteria. Hybrid LCA also performs well on the micro level. On the macro level MFA achieves the highest scores, closely followed by Hybrid LCA. Both methods show full compliance in the sub-criterion of data quality. P-LCA and EIO-LCA reach lower scores for all considered criteria and perform on the same level with regard to the methodological criteria.

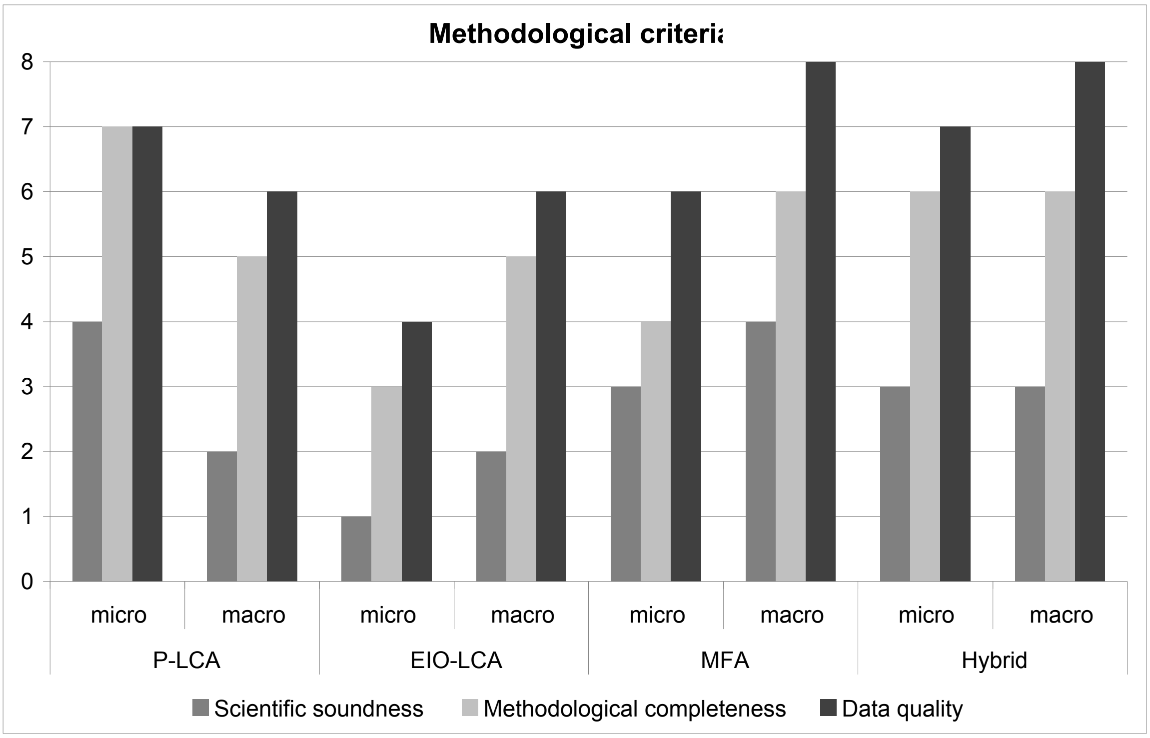


**Figure 12: Quantitative results of the methodological criteria**

## 4.3 Technical criteria

The technical criteria, which evaluate feasibility when applying the methods comprise three criteria:

- Availability of software tools, see 4.3.1
- Communicability of the method, see 4.3.2 and
- Data availability and accessibility, see 4.3.3

As for the general and the methodological criteria compliance of the methods with these criteria is evaluated on the sub-criteria level in the respective chapters. An overview of the results for the technical criteria is given in 4.3.4.

### 4.3.1 Availability of software tools

Compliance with the availability of software tools is evaluated by two sub-criteria:

- Number of available tools, see 4.3.1.1 and
- Variation in license models, see 4.3.1.2

The combined results of these two sub-criteria are shown in 4.3.1.3.

#### 4.3.1.1 Number of available tools

**Evaluation for P-LCA**

Tools are available on different levels of expertise. The tools can be used independently from the scope level. Compliance with the sub-criterion is complete for both levels. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 32.

**Evaluation for EIO-LCA**

There is a supply of simple-to-use internet tools as well as integration in experts LCA tools (SimaPro and CMLCA). The tools can be used independently from the scope level. Compliance with the sub-criterion is complete for both levels.

**Evaluation for MFA**

The calculation for an MFA is integrated in several expert tools while at the same it is possible to use an unspecific tool such as Excel. The tools can be used independently from the scope level. Compliance with the sub-criterion is complete for both levels.

**Evaluation for Hybrid LCA**

Inclusion in software (SimaPro) exists, but there are currently no simplified tools. The tools can be used independently from the scope level. Compliance with the sub-criterion is partially fulfilled for both levels.

**Table 32: Quantitative evaluation for the sub-criterion on the number of available tools**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Number of available tools | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 |

#### 4.3.1.2 Variation in licence models

**Evaluation for P-LCA**

Both free and commercial software tools are available; compliance with the sub-criterion is complete for both levels. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 33.

**Evaluation for EIO-LCA**

Both free and commercial software tools are available; compliance with the sub-criterion is complete for both levels.

### *Evaluation for MFA*

Both free and commercial software tools are available; compliance with the sub-criterion is complete for both levels.

### *Evaluation for Hybrid LCA*

Only commercial tools are available; compliance with the sub-criterion is partially fulfilled for both levels.

**Table 33: Quantitative evaluation for the sub-criterion on variation in license models**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Variation in licence models | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 |

## *4.3.1.3 Results on the criterion software tools*

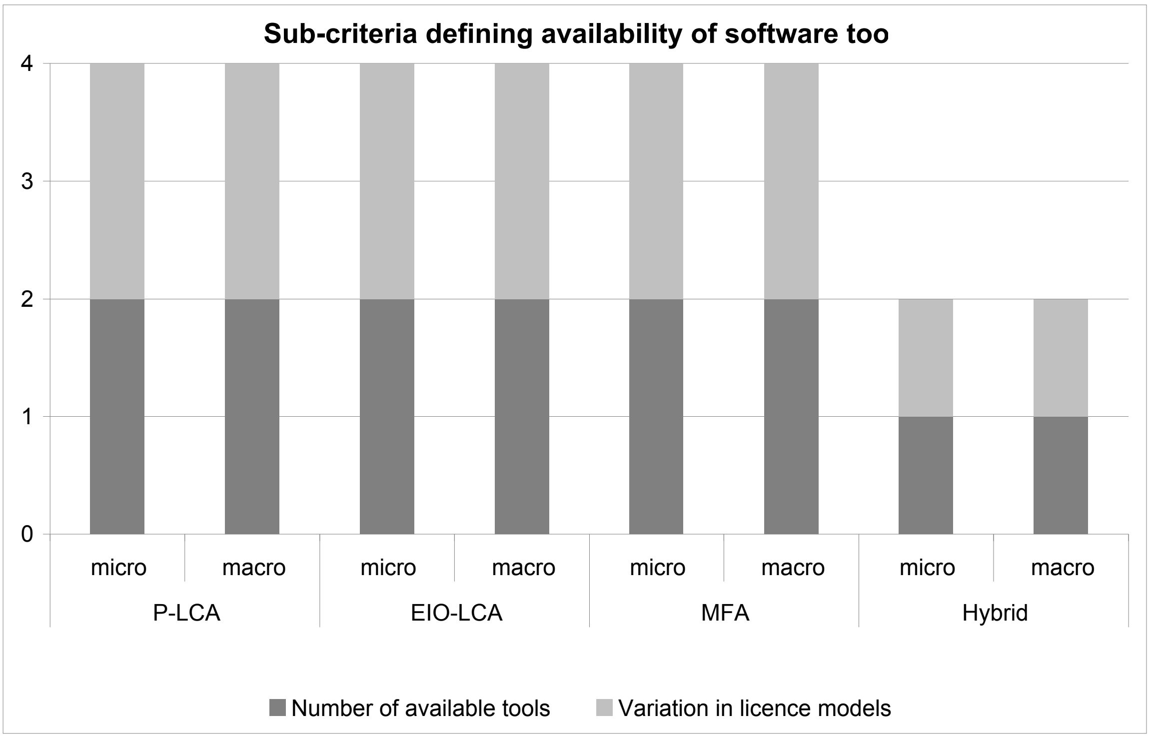


**Figure 13: Quantitative results of compliance with the availability of software tools, divided to the sub-criteria level**

Figure 13 shows the quantitative results for the availability of software tools which reveals that there are no discernable difference between the established methods P-LCA, EIO-LCA and MFA. Only Hybrid LCA achieves lower results, reaching only half of the possible score within this criterion.

### 4.3.2 Communicability of methods

The communicability of methods is described by the following sub-criteria:

- Clarity of method, see 4.3.2.1
- Comprehensible calculation and transparency, see 4.3.2.2 and
- Established communication, see 4.3.2.3

The combined results for these sub-criteria are additionally shown in 4.3.2.4.

#### *4.3.2.1 Clarity of method*

***Evaluation for P-LCA***

The basic concept behind P-LCA is simple, all phases are clearly described and connections apparent, but domain expertise is needed when applying the method. Results are often not unambiguous and need expert interpretation. On macro level clarity is additionally affected the extrapolation of process data which is neither entirely defined nor easily understood. On both levels compliance is therefore only partially fulfilled. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 34.

***Evaluation for EIO-LCA***

The basic concept behind EIO-LCA is simple. Connections between method steps are transparent. Parts of the methodology, however, are not easily comprehensible or connections logical, in particular connections between IO tables and environmental impacts and for micro level applications in general. Macro level analyses on the other hand are straightforward. For the macro level compliance is rated complete, on the micro level it is only partially fulfilled.

***Evaluation for MFA***

The basic concept of the method is simple. It delivers an unambiguous result and features logical and transparent connections. Compliance with the sub-criterion is complete for both levels.

***Evaluation for Hybrid LCA***

The methodology lays out ways to combine P-LCA and EIO-LCA, but is not simple due to the lack in clear procedures for the combination. Therefore also the result is not unambiguous and compliance cannot be found on either level.

**Table 34: Quantitative evaluation for the sub-criterion on clarity of method**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Clarity of method | 1 | 1 | 1 | 2 | 2 | 2 | 0 | 0 |

#### 4.3.2.2 Comprehensible calculation and transparency

##### Evaluation for P-LCA

Basic data is usually accessible (though this may be restricted depending on the used database and aggregation). Transparency is prerequisite and a principle, therefore also in data and relations. The calculation used in a study is usually documented and apparent. On the macro level accessibility is limited as mentioned above due to aggregation. Compliance is complete on the micro level and partially fulfilled on the macro level. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 35.

##### Evaluation for EIO-LCA

Calculation is well documented, though data is only accessible from a certain level of aggregation (inappropriate for micro level applications). Relations in data matrix require a certain economic knowledge, but are otherwise transparent. Compliance is complete on the macro level and partially fulfilled on the micro level.

##### Evaluation for MFA

MFA relies for a great part on statistical data and flow accounting. Accessibility to basic data is therefore dependent on specific situation, but in general provided. Calculation is well documented, both on macro and on micro level. Dependencies are apparent on macro level. On micro level, if focus is e.g. a single product, the actual dependencies are not apparent due to the nature of the method. Compliance is complete on the macro level and partially fulfilled on the micro level.

##### Evaluation for Hybrid LCA

Due to a diversity in approaches and calculations, transparency is comprehensible in individual applications, but less so for the method in general. Accessibility to data is similar to EIO-LCA and P-LCA and suffers from the same restrictions. Relations and dependencies are customisable in the model, therefore not generally apparent and comprehensible. Compliance is therefore rated as non-existent on both levels.

**Table 35: Quantitative evaluation for the sub-criterion on comprehensible calculation and transparency**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Comprehensible calculation and transparency | 2 | 1 | 1 | 2 | 1 | 2 | 0 | 0 |

#### *4.3.2.3 Established communication*

##### *Evaluation for P-LCA*

The method has been used for various fields of communication previously and several communication tools exist. (e.g., by publication of verified ISO type III EPDs for some relevant goods and services). These were carried out with regard to the audience and targeted communication type and show the adaptability. The European Union Eco-labelling board (EUEB) applies life-cycle considerations for the setting of criteria for labelling and is bound to follow the principles of ISO 14040 by the European regulation 1980/2000 [EC 2000]. Product groups, which have been assessed against this background, are therefore considered as macro level applications. They are communicated through the publication of the labelling criteria for these product groups. These have been carried out for e.g. different cleaning products and household appliances (see [CICAS ET AL. 2007] for details). Compliance is complete on both levels. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 36.

##### *Evaluation for EIO-LCA*

There are few examples of previous communication and no specific tools to do so, though the Ecoinvent centre gives some examples [ECOINVENT CENTRE]. In general, however, the compliance of the method for established practical communication is low and rated here as zero on both levels.

##### *Evaluation for MFA*

The method has been used for various fields of communication with regard to the audience and targeted communication type on the macro level and has been widely used in policy communication. Some companies reported MFA results in their CSR reports, which are examples for previous communication on the micro level (see e.g. [NIPPON 2007, NTT 2007]). In general the existence of previous communication is rated as complete on the macro level and as not fulfilled on the micro level.

***Evaluation for Hybrid LCA***

Previous communication of Hybrid LCAs is as yet not existent.

**Table 36: Quantitative evaluation for the sub-criterion on established communication**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Established communication | 2 | 2 | 0 | 0 | 0 | 2 | 0 | 0 |

#### *4.3.2.4 Results on the criterion communicability*

The results for the criterion on communicability are shown in Figure 14. It reveals that compliance of MFA on the macro level is the only one that is evaluated as complete, while on the micro level P-LCA performs best though its compliance is not complete. Hybrid LCA shows no compliance with the whole criterion.

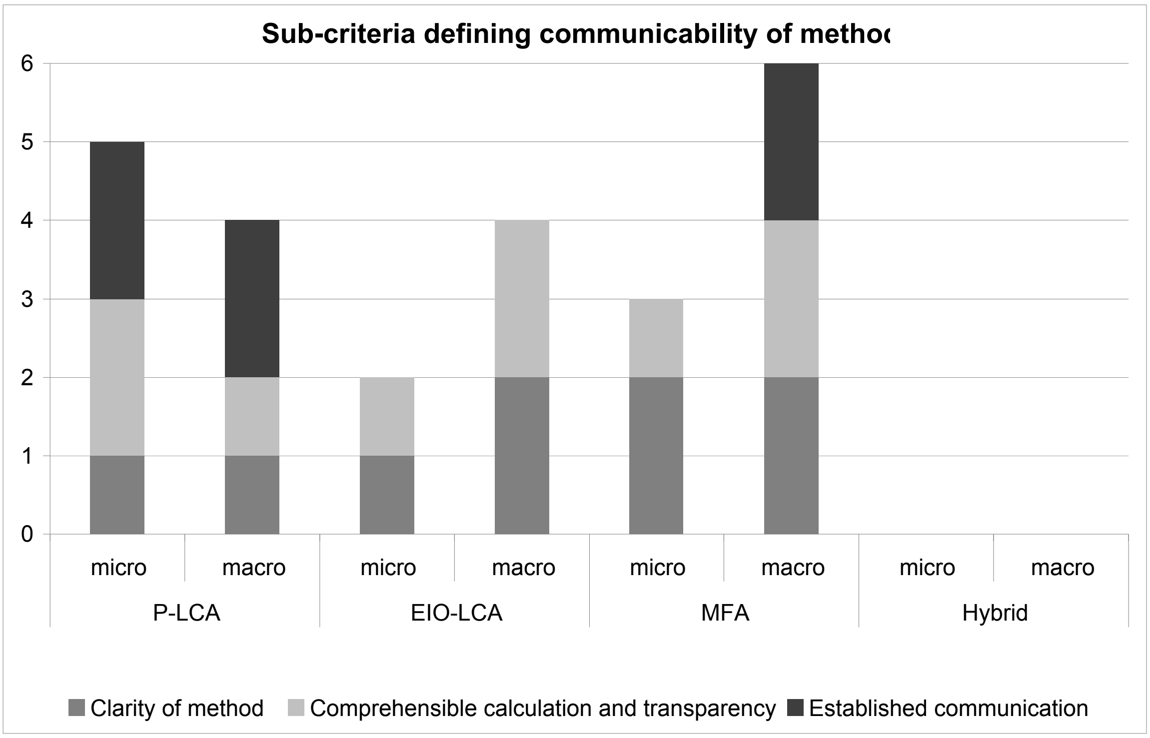


**Figure 14: Quantitative results of compliance with communicability of the methods, divided to the sub-criteria level**

### 4.3.3 Data availability and accessibility

The criterion for data availability and accessibility takes the following sub-criteria into account:

- Data coverage of the whole life cycle, see 4.3.3.1

- Availability of inventory data for different regions, see 4.3.3.2
- Availability of inventory data for all relevant impact categories, see 4.3.3.3 and
- Publicly accessible inventory databases at affordable cost, see 4.3.3.4

The evaluation of compliance of the methods with these sub-criteria is given in the referenced paragraphs, the evaluation for the whole criterion can be found in 4.3.3.5.

#### *4.3.3.1 Data coverage of the whole life cycle*

##### *Evaluation for P-LCA*

P-LCA data exists for all life cycle phases, though it may be hard to obtain in specific situations, but this is not a methodological issue. Compliance with data coverage is therefore rated as complete on both scope levels. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 37.

##### *Evaluation for EIO-LCA*

Data for EIO-LCA is not available for all life cycle phases. Manufacturing data is inherent in the IO tables and so is partly end-of-life data. Use-phase data is usually not included. On the micro level data availability is further affected by the necessary disaggregation which depends highly on the specific sector in EIO-LCA. For both levels compliance is rated as partially fulfilled.

##### *Evaluation for MFA*

Necessary data can be obtained for the whole life cycle on both scope levels; compliance is rated complete.

##### *Evaluation for Hybrid LCA*

The combination of the two basic LCA approaches provides a very good basis for data availability. In fact the enhancement of data availability is one of the major strengths of Hybrid LCA since missing data in one of the basic methods can be compensated by the other method.

**Table 37: Quantitative evaluation for the sub-criterion on the availability of data for the whole life cycle**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Availability of data for the whole life cycle | 2 | 1 | 1 | 1 | 2 | 2 | 2 | 2 |

#### *4.3.3.2 Availability of inventory data for different regions*

### *Evaluation for P-LCA*

Process-based data are collected for specific applications and regions or industry groups, but currently not all product or service data are collected for every region. If data are needed for different regions, the necessary up-scaling and averaging of data are possible with some unavoidable loss in quality. Compliance is rated partially fulfilled for both levels. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 38.

### *Evaluation for EIO-LCA*

Region-specific data are available and regional models are appearing [CICAS ET AL. 2007]. The availability of EIO-LCA data cannot be influenced by the LCA practitioner since data are provided mostly by government or other sources. Compliance is rated partially fulfilled for both levels.

### *Evaluation for MFA*

The availability of MFA data for different regions is one of the – method inherent – strong points on the macro level. As the method itself is focussed regionally, compliance is rated as complete for the purpose of this study even though not every single region worldwide is covered.

### *Evaluation for Hybrid LCA*

The combination of the two basic LCA approaches provides a very good basis for data availability. In fact, the enhancement of data availability is one of the major strengths of Hybrid LCA since missing data in one of the basic methods can be compensated by the other method, as stated above, which is also true for regional data. Compliance is therefore rated as complete on both levels.

**Table 38: Quantitative evaluation for the sub-criterion on the availability of inventory data for different regions**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Availability of inventory data for different regions | 1 | 1 | 0 | 1 | 2 | 2 | 2 | 2 |

#### 4.3.3.3 Availability of inventory data for all relevant impact categories

##### Evaluation for P-LCA

There is no limitation in the method concerning the availability of inventory data for impact categories usually applied and delivering a comprehensive picture. Compliance is therefore rated as complete on both levels. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 39.

##### Evaluation for EIO-LCA

The currently available inventory data is not entirely suitable for a comprehensive impact assessment including all relevant impact categories. Compliance is therefore rated as partially fulfilled both levels.

##### Evaluation for MFA

Though the impact assessment is not part of the method, MFA data can be used as a basis for an impact assessment and due to the focus on materials the data is suitable. Compliance is therefore rated as partially fulfilled on both levels.

##### Evaluation for Hybrid LCA

The combination of the two basic LCA approaches potentially provides a very good basis for data availability, but the lack of data on environmental issues to be used for the EIO-LCA part causes the compliance to be rated as only partially fulfilled on both levels.

**Table 39: Quantitative evaluation for the sub-criterion on the availability of inventory data for all relevant impact categories**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Availability of inventory data for all relevant impact categories | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 |

#### 4.3.3.4 Publicly accessible inventory databases at affordable cost

##### Evaluation for P-LCA

On the macro level databases are available and publicly accessible in different varieties, e.g., ecoinvent, the European ELCD and the German databases ProBas and Gemis [ECOINVENT DATA, GEMIS, JRC-IES 2009, PROBAS]. On the micro level accessibility is more restricted since company-specific data are usually less likely to be publicly accessible. Compliance is rated as non-existent on the micro level and complete on the macro level. The quantitative scores of P-LCA and the other methods for this sub-criterion are shown in Table 40.

### *Evaluation for EIO-LCA*

EIO-LCA is publicly accessible and free, but accessibility to the micro level is inherently restricted. Compliance is rated as non-existent on the micro level and complete on the macro level.

### *Evaluation for MFA*

Material flow accounts that are used for MFA are publicly accessible. Micro level data is not part of databases. Compliance is rated as non-existent on the micro level and complete on the macro level.

### *Evaluation for Hybrid LCA*

Due to combination of EIO-LCA and P-LCA accessibility of databases for Hybrid LCA is complete on the macro level and as limited on the micro level as it is for the two basic LCA approaches. Compliance is rated as non-existent on the micro level and complete on the macro level.

**Table 40: Quantitative evaluation for the sub-criterion on publicly accessible inventory databases at an affordable cost**

| Sub-criterion | P-LCA | | EIO-LCA | | MFA | | Hybrid-LCA | |
|---|---|---|---|---|---|---|---|---|
| | Micro | Macro | Micro | Macro | Micro | Macro | Micro | Macro |
| Publicly accessible inventory databases at affordable cost | 0 | 2 | 0 | 2 | 0 | 2 | 0 | 2 |

### *4.3.3.5 Results on the criterion data availability and accessibility*

Figure 15 shows that none of the methods reach full compliance with the criterion on data availability for either scope level. MFA, P-LCA and Hybrid all show the same high compliance with the criterion on the macro level, and the same though significantly lower compliance on the micro level. EIO-LCA scores lower than the other considered methods on both levels.

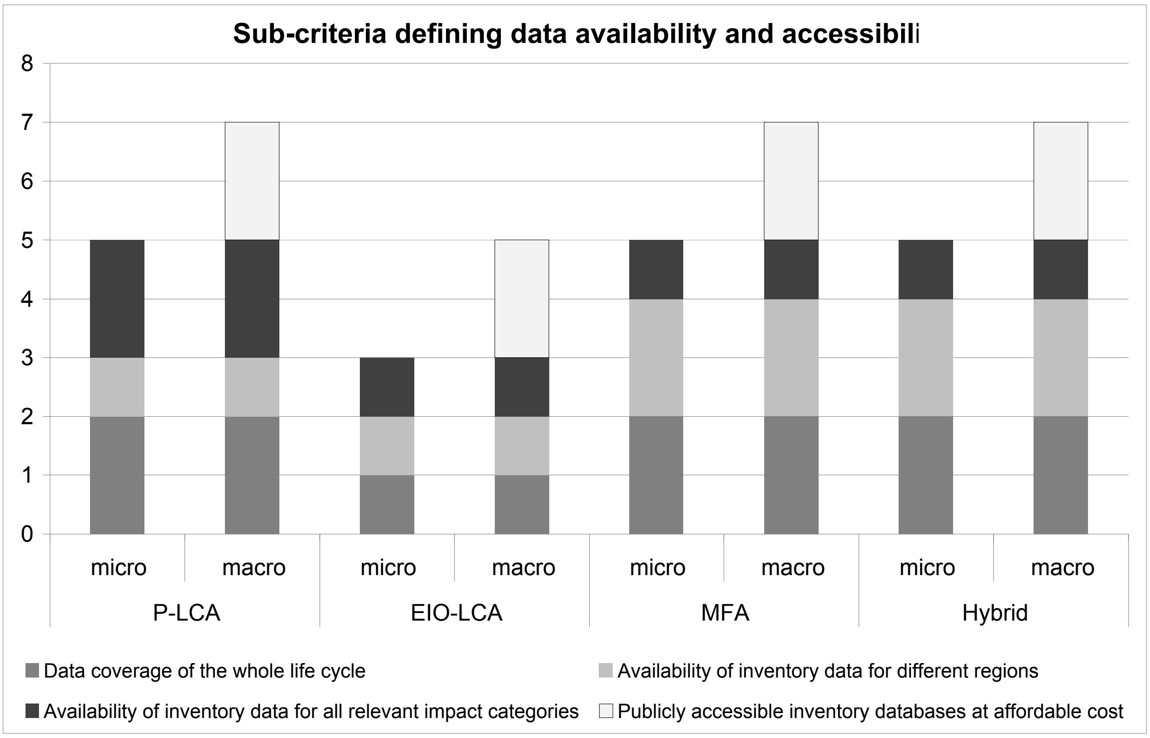


**Figure 15: Quantitative results of compliance with data availability and accessibility, divided to the sub-criteria level**

### 4.3.4 Overall result of the technical criteria

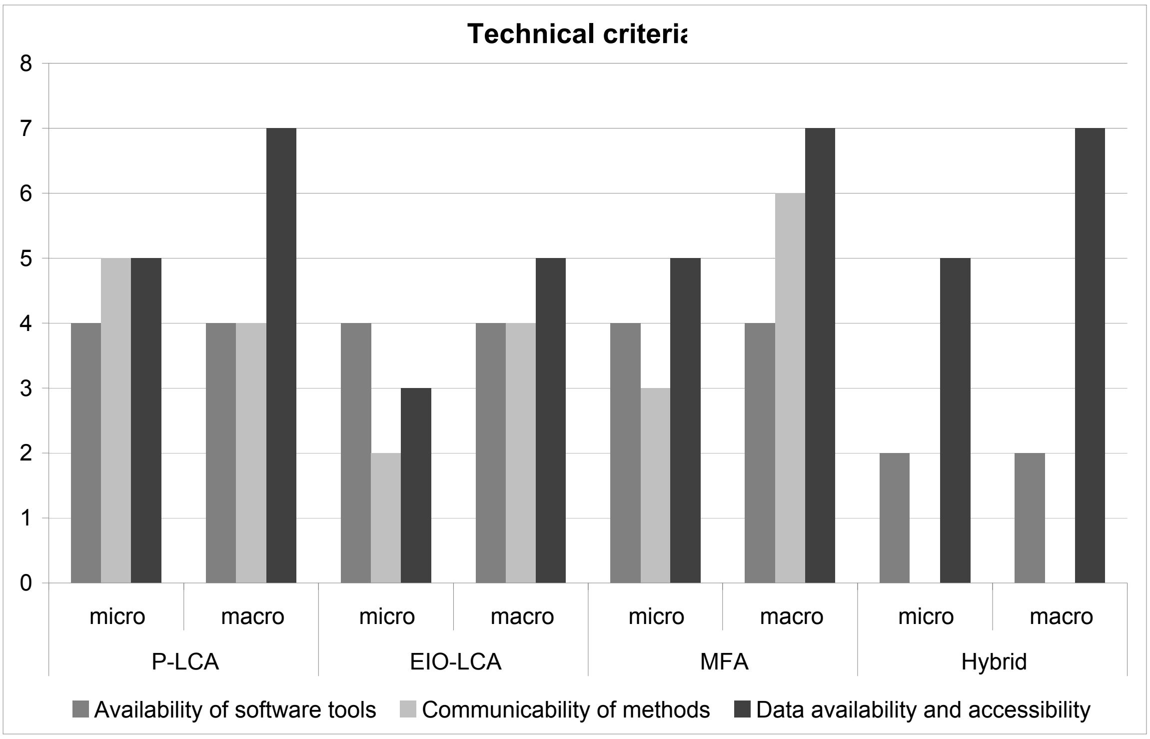


**Figure 16: Quantitative results of the technical criteria**

The results for the technical criteria on the criteria level are shown in Figure 16. On the micro level they reveal again the best compliance for P-LCA, followed by MFA which scores different from P-LCA only in one of the criteria. On the macro level it is the other way around, with MFA showing the highest compliance, followed by P-LCA and scores differing only for one criterion. EIO-LCA achieves lower compliance than P-LCA and MFA on both levels except for the criterion on software tools. Hybrid LCA reveals the lowest overall compliance with the technical criteria even though its data availability and accessibility are comparative.

## 4.4 Summary of the evaluation

The scores were awarded on the level of the sub-criteria in the previous paragraphs. These sub-criteria were used as a tool to make the evaluation more transparent. However, the implications of these results are to be shown and discussed on the criteria level. As there are different numbers of sub-criteria for the criteria the results on the criteria level were transformed to show the percentage of compliance with the criteria for each method. Table 41 and Table 42 show this percentaged compliance.

**Table 41: Compliance of the life cycle method with each criterion on the micro level, in percent**

| Criteria | Compliance on the micro level [%], for | | | |
|---|---|---|---|---|
| | P-LCA | EIO-LCA | MFA | Hybrid LCA |
| Method documentation | 100 | 33 | 17 | 33 |
| Applicability | 100 | 50 | 50 | 100 |
| Stakeholder acceptance | 83 | 17 | 0 | 17 |
| Objectivity | 50 | 50 | 75 | 25 |
| Scientific soundness | 100 | 25 | 75 | 75 |
| Methodological completeness | 88 | 38 | 50 | 75 |
| Data quality | 88 | 50 | 75 | 88 |
| Availability of software tools | 100 | 100 | 100 | 50 |
| Communicability of methods | 83 | 33 | 50 | 0 |
| Data availability and accessibility | 63 | 38 | 63 | 63 |

On the micro level P-LCA shows the highest compliance with the criteria taken into account here reaching more than 50 % of the scores in all cases and a 100% in four criteria. EIO-LCA, MFA and Hybrid LCA reach full compliance in one criterion each but achieving 50% or less in several. However, they, too, show strong performance in some respects. The implications of these results will be discussed in chapter 6.

On the macro level the result is more diverse. P-LCA, EIO-LCA and MFA all reach at least 50 % in all criteria; MFA achieves full compliance in four criteria. Only Hybrid LCA is evaluated with a score lower than 50% for several criteria, though it still shows strong compliance in others. Again, these results will be discussed in chapter 6.

**Table 42: Compliance of the life cycle method with each criterion on the macro level, in percent**

| | Compliance on the macro level [%], for | | | |
|---|---|---|---|---|
| Criteria | P-LCA | EIO-LCA | MFA | Hybrid LCA |
| Method documentation | 67 | 83 | 67 | 33 |
| Applicability | 75 | 75 | 50 | 100 |
| Stakeholder acceptance | 67 | 50 | 50 | 17 |
| Objectivity | 50 | 75 | 75 | 25 |
| Scientific soundness | 50 | 50 | 100 | 75 |
| Methodological completeness | 63 | 63 | 75 | 75 |
| Data quality | 75 | 75 | 100 | 100 |
| Availability of software tools | 100 | 100 | 100 | 50 |
| Communicability of methods | 67 | 67 | 100 | 0 |
| Data availability and accessibility | 88 | 63 | 88 | 88 |

It shall be noted that as some subjectivity cannot be entirely avoided when applying quantitative scores on the basis of qualitative aspects, consulting leading experts in the fields of the respective methods added additional value and credibility. While this does not mean that different experts would not assign different scores, the transparent evaluation scheme and the justification of each score allow traceability of the quantitative results which are used for qualitative discussion and conclusions.

The results of the theoretical evaluation of P-LCA, MFA, EIO-LCA and Hybrid LCA are concluded with this chapter. Chapter 5 will describe additional case studies which were performed to add practical information to the information gained from the theoretical evaluation and will be taken into account for the discussion in chapter 6 as well.

# 5 Case studies

In the previous chapter the considered life cycle methods were evaluated against their compliance with the criteria scheme developed in chapter 3. In addition to the theoretical evaluation of the methods' suitability for micro and macro level applications several case studies were conducted within the framework of this thesis. The aim of these case studies is to cross-check the results of the theoretical evaluation as well as to provide additional insights where evaluation criteria were found to be case dependent.

The case studies were performed applying EIO-LCA and P-LCA. These two methods were selected as they form extreme alignments of life cycle assessment with the focus on processes of P-LCA on one end and the focus on sector averages of EIO-LCA at the other. Hybrid LCA is situated somewhere in between these two methods but its methodology was found to be not clearly defined yet and thus susceptible to assumptions and specific decisions by the user. As this study aims to provide information on the applicability on a general basis, no case studies were performed for Hybrid LCA.

As stated in the introduction MFA was included in the overall study because it was expected to be able to provide a basis for an environmental impact assessment even though it does not include one on the methodological level. For this reason it was excluded from the case study analysis.

For these analytical reasons the following case studies were applied to P-LCA and EIO-LCA only. Furthermore the choice of the case studies themselves was based on the availability of reliable and consistent data, which necessitated as little additional modelling as possible as this might introduce further value choices independent from the method inherent ones.

## 5.1 Employed data

Data used for the case studies was taken from two main sources, one for P-LCA and one for EIO-LCA. These contain highly aggregated and averaged data and not, for instance, company specific data. The choice of databases means that the conducted case studies represent applications on the macro level. The only exception to this is the case study on an aluminium composite material for which existing process-based data could be used. This case study is expected to provide information how well an EIO-LCA database corresponds to process-specific data on the micro level.

### 5.1.1 E3IOT database

The commercial E3IOT database was used to conduct the EIO-LCA analyses [CML]. This table provides an environmentally extended IO table for Europe, covering production, consumption and waste management. The model is described in detail by HUPPES (2008), features relevant for this thesis are described here in short, all information given here is gathered from this reference [HUPPES ET AL. 2008].

The functional unit within the model is the total domestic final demand for each product consumed in the EU-25. This means that the impacts caused by production of goods in Europe is included but also those related to the production of imported goods, the use and waste management of products.

For the EU typical IO tables are not disaggregated enough to allow for detailed LCA studies. Therefore the US IO table with its much higher resolution was used as basis for the model. The US table was Europeanised using a mathematical method that is commonly used to calculate estimates of IO tables from similarly structured IO data. The underlying European data originates from OECD country data of 1990, which was extrapolated to the EU-25 level of 2003. Furthermore data for the use and end-of-life phase was derived from other LCA databases and added to provide a basic coverage of these phases of the life cycle. It is to be noted, however, that intermediate products will not cover the whole life cycle, but rather be cradle-to-gate as waste management is connected to final demand. From a methodological point of view the model is therefore not a pure EIO-LCA model, but cannot be viewed as a Hybrid model either as it does not fulfil the definitions for either the tiered hybrid approach or the integrated hybrid analysis given in 2.4.

These adaptations transformed the original OECD table, which contained 35 sectors into a model with 965 sectors, covering production, use and basic waste management scenarios.

### 5.1.2 ELCD database

Data for the P-LCA analyses was retrieved from European Life Cycle Database (ELCD) database provided by the Joint Research Centre of the European Commission [JRC-IES 2009]. The contained data sets are mainly supplied by European business associations and can be used free of charge. It includes data on materials, energy carriers, transport and waste management and will be updated with additional data sets as they become available. Each data set is documented in detail, giving information on e.g. the data source, technological coverage, geographical representativeness, applied allocation rules and conducted reviews. Therefore the base year or the coverage of life cycle stages cannot be stated in general as for the E3IOT database, but will instead be provided in the respective system descriptions.

### 5.1.3 Data for the impact assessment

Both databases contain methods for an impact assessment, but showed slight differences in the underlying information, e.g. on characterisation factors, for the methods. The method applied here was adjusted so as not to introduce additional uncertainties in the comparison. Information for the impact assessment was therefore taken from GUINÉE (2002) as the authoritative source describing the often-applied so-called CML method [GUINÉE 2002]. GUINÉE (2002) classifies the different impact categories into baseline, study-specific and other impact categories. For this study the baseline impact categories were chosen as they are well established with regard to acceptance and characterisation model[1], they are shown in Table 43.

**Table 43: Selected impact categories**

| Impact category | Indicator result |
|---|---|
| Depletion of abiotic resources | Abiotic Depletion Potential – ADP (in kg antimony eq.) |
| Climate Change | Global Warming Potential – GWP 100 (in kg $CO_2$ eq.) |
| Stratospheric Ozone Depletion | Ozone Depletion Potential – ODP (in kg CFC-11 eq.) |
| Human Toxicity | Human Toxicity Potential – HTP (in kg 1,4-dichlorobenzene eq.) |
| Freshwater Aquatic Ecotoxicity | Freshwater Aquatic Ecotoxicity Potential – FAETP (in kg 1,4-dichlorobenzene eq.) |
| Marine Aquatic Ecotoxicity | Marine Aquatic Ecotoxicity Potential – MAETP (in kg 1,4-dichlorobenzene eq.) |
| Terrestrial Ecotoxicity | Terrestrial Ecotoxicity Potential – TETP (in kg 1,4-dichlorobenzene eq.) |
| Photo-Oxidant Formation | Photochemical Ozone Creation Potential – POCP (in kg ethene eq.) |
| Acidification | Acidification Potential – AP (in kg $SO_2$ eq.) |
| Eutrophication | Eutrophication Potential – EP (in kg $PO_4$ eq.) |

## 5.2 Description of the case study systems

The selection of the case studies is based on several aspects. As the two mainly employed data source are the ELCD database and the E3IOT database potential case studies had to be included in these. At the same time they should cover different material groups to avoid that results might be misleading and in fact only be applicable to a specific material group. The two main material groups chosen are plastic materials and metals. From the metals group copper was selected; see 5.2.1, as it is included in the ELCD database as well as a specific

[1] Note that land competition was not included, even though it is listed as a baseline impact category by GUINÉE (2002). The model for land competition contains a relation to time which is not modelled in P-LCA

sector in the E3IOT database. From the plastics group 4 different plastics were chosen, see 5.2.2, which are all included in the ELCD database, though only as a general sector in the E3IOT database. In contrast to the case study on copper, the plastics related case study is therefore expected to provide information on obtainable results when the sectors included in EIO-LCA cover a broad range of products and how they might differ from results obtained from narrowly defined sectors as in the case of copper. These case studies represent macro level applications as they focus on the average situation in Europe.

The last case study on an aluminium composite material, see 5.2.3 was, selected as it combines the two material groups “metals” and “plastics” but is modelled with site specific data for P-LCA and can therefore be used to evaluate how results obtained from such data compares to the general data of pure EIO-LCA. This last case study fits in the micro level scope as a specific product is evaluated.

### 5.2.1 Copper sheet in the EU-15

The data set used for the P-LCA analysis originates from the ELCD database, its full name is “Copper sheet; technology mix, consumption mix, at plant; 0,6 mm thickness” [JRC-IES 2009]. The data provides a cradle to gate scenario for the production of copper sheet as used by end consumers and includes the end of life recycling of the material. Copper production is modelled for the EU while upstream processes such as copper mining are global or European averages. The reference year of the data is 2000. Necessary allocation (for e.g. gold and nickel) was done according to market value. The analysis was carried out for the production of 1000 kg of copper sheet.

EIO-LCA was conducted using the E3IOT model, which includes several sectors containing copper: “copper ore”, “primary smelting and refining of copper”, “rolling, drawing and extruding of copper”, “consumption phase of copper ore”, “consumption phase of primary smelting and refining of copper, “consumption phase of rolling, drawing and extruding of copper” and the waste sector “scrap (metal recycling)”. The sector for the consumption of rolling, drawing and extruding of copper was chosen for the analysis; even the P-LCA data set does not contain consumption. However, doing so ensures that the end-of-life stage of the material is included in the EIO data as it is included in the P-LCA and the consumption sector of refining copper is not expected to have a significant impact on the environmental results. Furthermore, as only consumer prices could be obtained for copper sheets the use of the consumption sector seems more consistent. Prices for copper sheets are susceptible to change, so the price used here is taken for a specific time, namely April 2010, for which an average of 90 EUR/$m^2$ was researched (average of several suppliers at the time). With an approximate mass of 5,5 kg/ $m^2$ for the copper sheet of 0,6 mm thickness, the cost responding to 1000 kg of copper sheet is around 16400 EUR.

### 5.2.2 Production of plastics materials in Europe

In order to be able to compare the environmental impacts of products which are likely to be found in one common sector of an IO table, four different plastics were selected. The selection was done with the intent to analyze differences in plastics materials regarding two basic features: the plastics should cover a range of complexity in the materials, from basic plastics to more sophisticated ones, but should at the same time include plastics of very similar quality, estimated as primary energy demand. The selected plastics are therefore:

- Polyethylene High Density granulate (PE-HD), primary energy demand of approx. 72 MJ
- Polyethylene Low Density granulate (PE-LD), primary energy demand of approx. 74 MJ
- High impact polystyrene granulate (HIPS), primary energy demand of approx. 83 MJ
- Polyamide 6.6 granulate (PA 6.6), primary energy demand of approx. 132 MJ

The data obtained from the ELCD database originates from the same source for all four plastics and is averaged based on data by European suppliers. Reference years vary between 1996 and 2002. It represents the production mix at the plant in all cases, all data is provided for the production of 1 kg of the respective plastic. The names of the used data sets are as follows:

- Polyethylene high density granulate (PE-HD); production mix, at plant
- Polyethylene low density granulate (PE-LD); production mix, at plant
- High impact polystyrene granulate (HIPS); production mix, at plant
- Nylon 66 granulate (PA 66); production mix, at plant

The E3IOT database contains several sectors with reference to plastics: “plastics materials and resins”, “rubber and plastics footwear”, “miscellaneous plastics products, n.e.c.”, “rubber and plastics hose and belting”, their respective sectors within the consumption phase and the end-of-life phase “scrap (plastic recycling). As all except the first one refer to specific consumer products, the sector “plastic materials and resins” is selected as the one for the comparison with granulate production from the ELCD database. In this case the production sector is used as basis (unlike for the copper sheets) as the ELCD also refers to the production of the materials.

Data on the prices of these plastics was retrieved from Plastics Information Europe, which researches plastic prices from plastic converters, producers, distributor and trade [PLASTICS INFO 2009]. The price is an average of that paid by large consumers in Western Europe.

In order to account for the influence price fluctuation may have on EIO-LCA results; two different prices are considered for the plastics analyses: the one from April 2010 and the one from April 2009. These are shown in Table 44.

**Table 44: Plastic prices used for the calculation in EIO-LCA [PLASTICS INFO 2009]**

| Plastics | Price of April 2010 | Price of April 2009 | April 2009/April 2010 |
|---|---|---|---|
| PE-HD | 1,2 EUR/kg | 0,91 EUR/kg | 76 % |
| PE-LD | 1,3 EUR/kg | 0,92 EUR/kg | 71 % |
| HIPS | 1,6 EUR/kg | 1,1 EUR/kg | 69 % |
| PA 6.6 | 3,3 EUR/kg | 2,95 EUR/kg | 89 % |

### 5.2.3 Aluminium composite material

For the fourth case study an aluminium composite material used in the building sector was analysed. The environmental data is provided by an Environmental Product Declaration [ALCAN 2009]. Data for the P-LCA is not taken from the ELCD database but consists of average background data as found in the GaBi database [GaBi] and site-specific data. The analysis covers the entire life-cycle including material production, manufacturing, the use phase, recycling and transport processes. The product consists mainly of aluminium and PE-LD. For the final product 3,165 kg aluminium and 3,18 kg PE-LD are employed. For the purpose of this study the composition was simplified by leaving out the lacquer coating part of the aluminium as not market data could be obtained for this and its proportion in the end product is minimal.

As the life cycle of the composite material shows a significant influence of the recycling phase and it is assumed that this will not be reflected adequately by the basic waste management information included in the E3IOT database, two different systems have been taken into account for P-LCA: one covering the whole life cycle, including recycling and one covering only production, assembly and use of the product.

For the conduction of EIO-LCA again the E3IOT database was used. The sectors including plastics are listed in 5.2.2 and again the sector of “plastic materials and resins” is selected as the other comprise of household products, which will not contain this product from the building sector. However, in contrast to the previous analysis of pure plastic materials, this time the consumption sector of “plastic materials and resins” is used in order to match it more closely to the data contained in the P-LCA study.

Aluminium can be found in seven sectors within the E3IOT database: “primary aluminium”, “aluminium rolling and drawing”, “aluminium castings”, their respective sectors for the consumption phase and the end-of-life phase “scrap (metal recycling)”. The aluminium sheet used for the composite material will be included in the sector “aluminium rolling and drawing”, again the sector for the consumption phase is selected.

Prices for the two materials are again based on the state of April 2010, so for PE-LD the same price as in paragraph 5.2.2 is assumed: 1,3 EUR/kg [PLASTICS INFO 2009]. The price for aluminium is taken from which stated it to be 1,7 EUR/kg on average in April 2010. In combination with the above-mentioned mass of the materials the price used for PE-LD amounted to 4,13 EUR, the price for aluminium to 5,38 EUR.

## 5.3 Results of the case studies

The results will be checked per impact category for their dominating contributions. For EIO-LCA it will also be shown which sectors are most relevant for the environmental impacts. This differentiation cannot be given for P-LCA. An overview of the impact assessment results is given in Annex 2.

The results of the impact assessment were not normalised on regional data as is often done, but rather normalised to each other in order to eliminate the different magnitude in the indicator results which is not of importance for the purpose of this study. No decision relating to the choice of a certain material or product is intended but rather the comparison between the methods themselves.

### 5.3.1 Copper sheet in the EU-15

For most impact categories EIO-LCA reveals significantly higher results than P-LCA as can be seen in Figure 17, the magnitude in the difference of results ranging from a factor of 100 to 10000. The exceptions to this are the results for the Abiotic Depletion Potential and the Eutrophication Potential where P-LCA calculations reveal a higher impact. For the other impact categories the quantitative P-LCA result reaches a maximum of 2% of that of EIO-LCA.

The reason for the lower ADP can be explained by the data contained in the E3IOT database itself: it only takes into account fossil energy extractions and leaves out extraction of other resources as European resource extraction is limited [HUPPES ET AL. 2008]. Indeed, the fossil energy extractions contribute most to the ADP result of P-LCA as well though the quantitative result for P-LCA would be higher than that for EIO-LCA even if only the fossil fuel extractions were considered in both methods.

The differences in all other impact categories have less obvious reasons. In the following paragraphs the results in each impact category are checked as to why differences between the methods may occur.

### *GWP*

The GWP is most influenced in both methods by the emission of carbon dioxide and methane. The sector emitting the highest amount of emission relevant to GWP within the EIO-LCA calculation is the sector of “electric services (utilities)”, followed by the sector of “blast furnaces and steel mills” and the one of “rolling, drawing and extruding of copper”, which was used as basis for the calculation itself.

### *ODP*

To ODP trichlorofluoromethane (R11) and dichlorodifluoromethane (R12) have the highest contributions, stemming mainly from the sectors “industrial inorganic and organic chemicals” and “nonwoven fabrics” within EIO-LCA. Methyl chloride and R11 show the highest contribution for ODP within P-LCA.

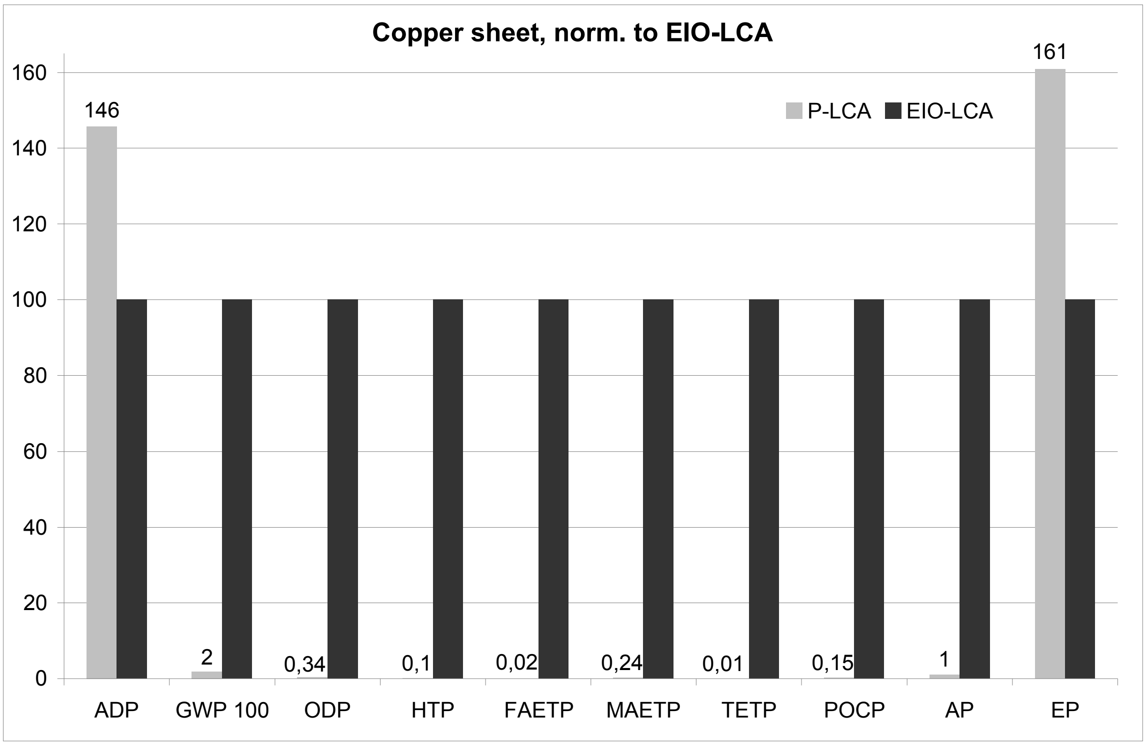


**Figure 17: Results for copper sheet, normalised to EIO-LCA**

### HTP

Thallium has the highest contribution to HTP within EIO-LCA, stemming from “non ferrous metal ores”. This difference between the methods is highly significant as the P-LCA data does not assume a thallium emission at all; on the contrary it calculates a credit for the metal. Within the P-LCA calculation hydrogen fluoride and nickel have the highest impact on HTP, though the magnitude of both emissions is far surpassed by that in EIO-LCA.

### FAETP

The impact on FAETP is mainly caused by the emission of acrolein in EIO-LCA which originates in the sector of “plastic materials and resins”. In P-LCA vanadium and nickel show the highest contribution.

### MAETP

For MAETP hydrogen fluoride causes the highest contribution in both methods. The IO sectors contributing the most are “blast furnaces and steel mills” and “coal”.

### TETP

TETP is most influenced by the emission of chromium and mercury in EIO-LCA and P-LCA. The sector contributing the most to the emission of chromium in EIO-LCA is “copper ore”.

### POCP

Unspecified non-methane volatile organic compounds (NMVOC) contribute most to the category of POCP within the application of both methods. The sectors with the greatest influence on the emission of these are “rolling, drawing and extruding of copper” and “industrial inorganic and organic chemicals” within EIO-LCA.

### AP

For AP sulphur dioxide and nitrogen dioxide are of greatest influence within both LCA models and “primary smelting and refining of copper” as well as “electric services (utilities)” are the sectors with the highest contributions within EIO-LCA.

### EP

Nitrogen (N compounds) and nitrogen dioxide show the highest contribution to EP within the P-LCA application. Nitrogen is not accounted for by EIO-LCA but nitrogen dioxide has the greatest impact while “rolling, drawing and extruding of copper” as well as “electric services (utilities)” are the most contributing sectors.

### 5.3.2 Production of plastics materials in Europe

The emission and sectors most contributing to EIO-LCA can be given for all four plastics as a whole, as they will only differ in quantity, not in quality. The reason for this is that all four plastics materials are attributed to one sector within the database for EIO-LCA. Therefore the associated sectors and emissions are the same ("quality") but the resulting amount of each emission or contribution of a sector ("quantity") depends on the price of the material. As the four plastic materials have different prices the amount of emissions and sector contribution will differ, too. For P-LCA each plastic material is analysed individually for most influential emissions.

As is apparent for the results of the copper sheet the results for EIO-LCA are higher in most impact categories, with the exception of ADP, see Figure 18, for all four plastics and EP for PA 6.6, see Figure 26. The results in both methods are dominated by the extraction of crude oil and hard coal for AP though the quantitative result for P-LCA would be higher than that for EIO-LCA even if only the fossil fuel extractions were considered in both methods.

In the following paragraphs the results in each impact category are checked as to why differences between the methods may occur.

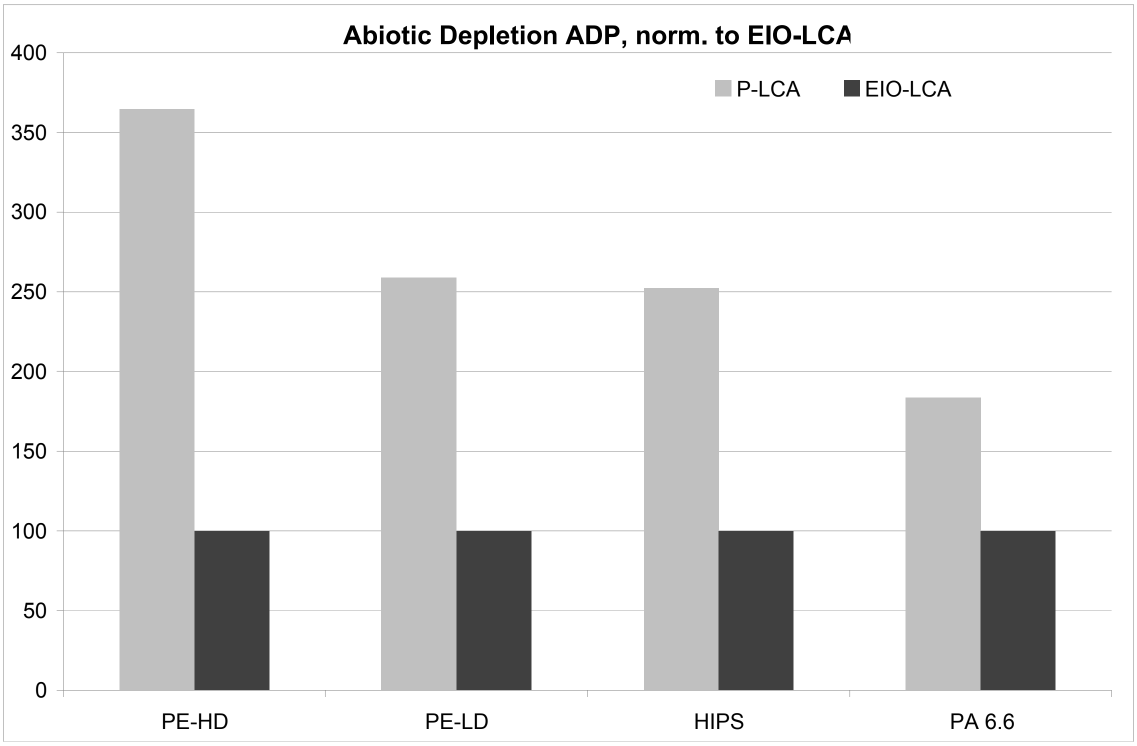


**Figure 18: Results of ADP, normalised to EIO-LCA (high price)**

### *GWP*

The GWP result of the EIO-LCA application is dominated by R12 and carbon dioxide, with the sectors of "plastics materials and resins" (the basis of the analysis), "industrial inorganic and organic chemicals" and "electric services (utilities)" having the highest influence. Within the P-LCA results carbon dioxide shows the highest contribution, R12 is not apparent as emission. The quantitative of the GWP impact calculated by P-LCA reaches approximately 40 to 70 % of the EIO-LCA result calculated with the higher price, see Figure 19.

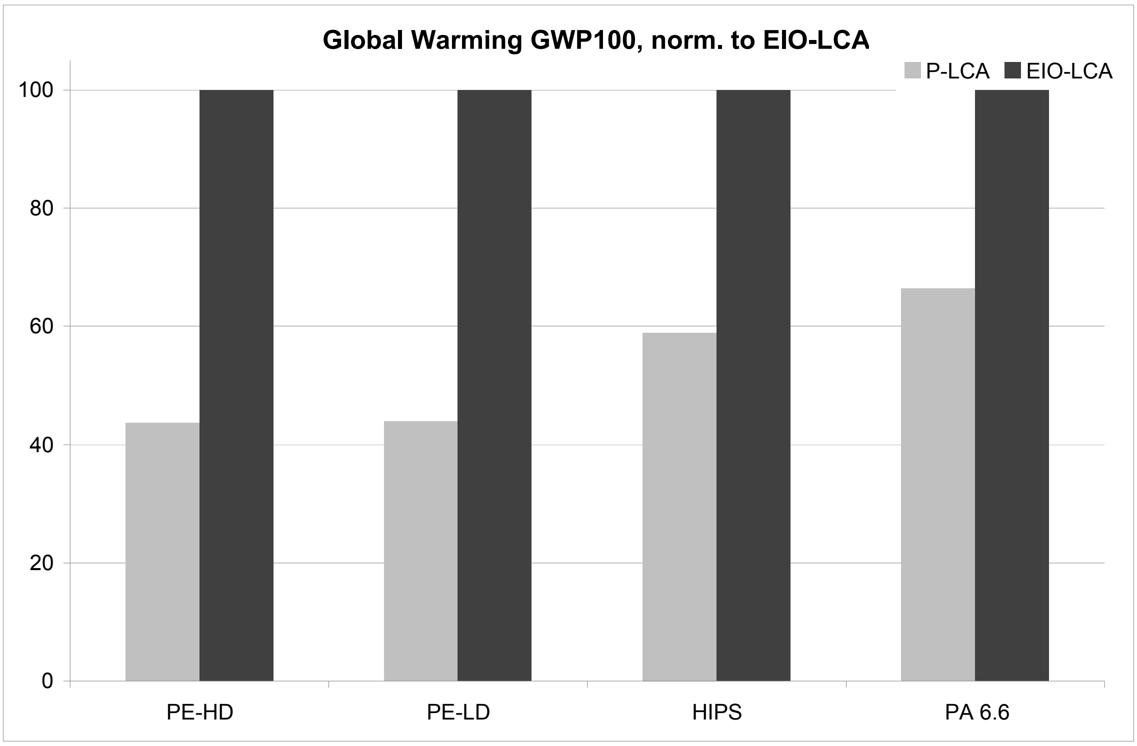


**Figure 19: Results of GWP, normalised to EIO-LCA (high price)**

### *ODP*

R11 and R12 mainly contribute to the EIO-LCA results of ODP, again originating from the sectors of "plastics materials and resins" and "industrial inorganic and organic chemicals". For P-LCA no contribution to ODP is discernible for any of the plastics materials.

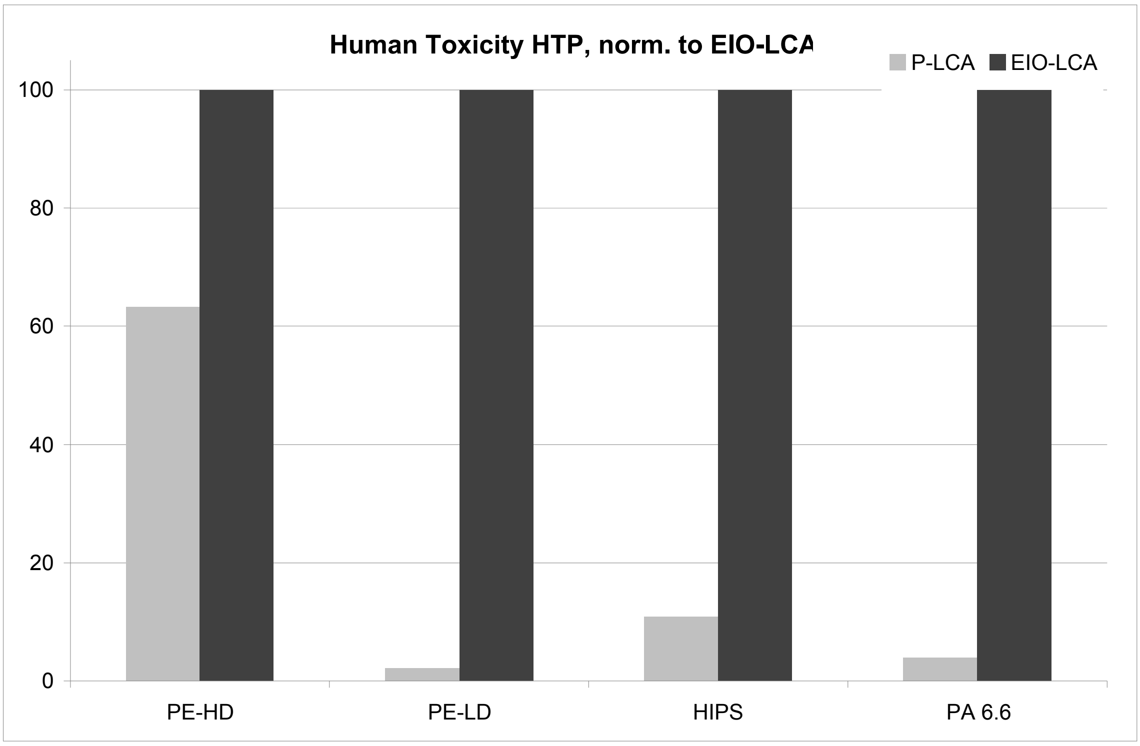


**Figure 20: Results of HTP, normalised to EIO-LCA (high price)**

### *HTP*

For the HTP result of EIO-LCA beryllium has the highest influence, originating from the sectors of “plastics materials and resins” and “industrial inorganic and organic chemicals”. The result of the P-LCA analyses is more diverse, though similarities occur. For PE-HD the single most contributing emission is the dioxin 2,3,7,8-TCDD, for HIPS it is nickel. The contribution of PA 6.6 is dominated by nickel and hydrogen fluoride and PE-LD by vinyl chloride and hydrogen fluoride. A contribution of beryllium to the P-LCA result is not discernible at all. The comparison of the quantitative HTP result differs between the plastics: while the result calculated by P-LCA amounts to less than 10 % of the EIO-LCA result calculated with the higher price for PE-LD, HIPS and PA 6.6, it reaches more than 60 % for PE-HD, see Figure 20.

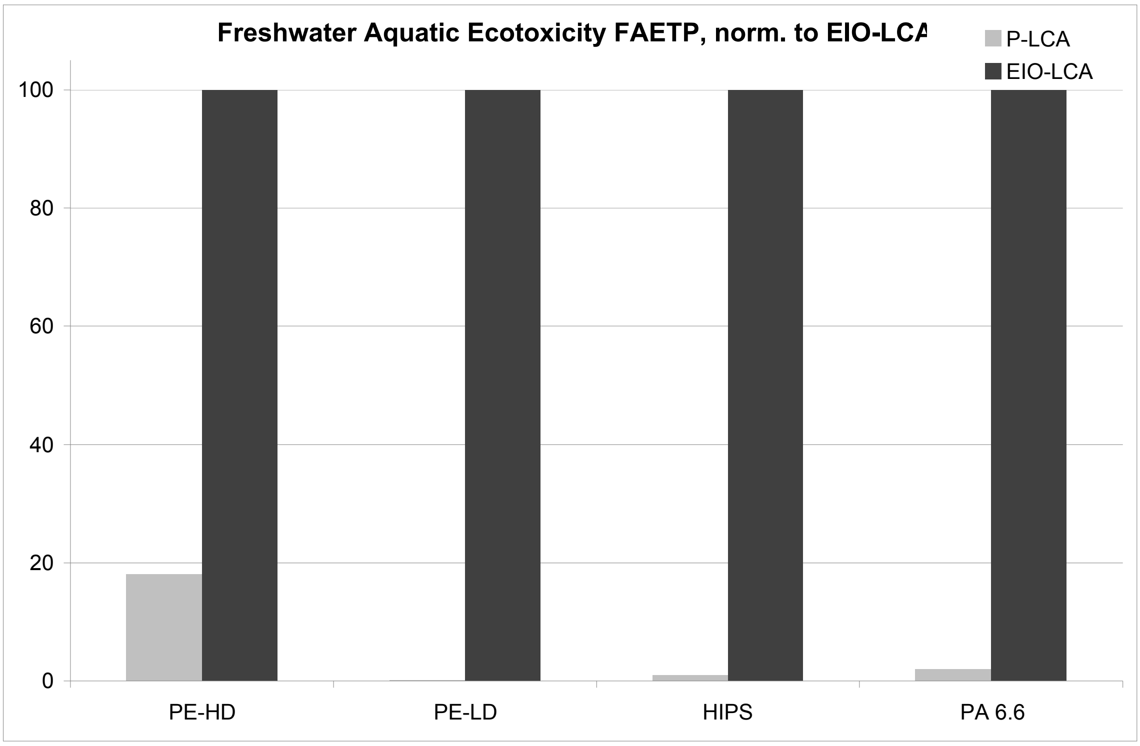


**Figure 21: Results of FAETP, normalised to EIO-LCA (high price)**

### *FAETP*

Acrolein is almost entirely the cause of EIO-LCA's impact on FAETP, originating from the sectors of "plastics materials and resins" and "industrial inorganic and organic chemicals". Acrolein is not apparent within the results of P-LCA. The result of the P-LCA analyses is more diverse, though similarities occur. For PE-HD the single most contribution emission is the dioxin 2,3,7,8-TCDD. Contributions of PE-LD to FAETP stem from copper and phenol, while copper and nickel contribute most for HIPS and PA 6.6. As for HTP PE-LD calculated by P-LCA shows a higher impact in comparison to the other plastics, arriving at nearly 20% of the EIO-LCA result calculated with the higher price, while the other plastics' impact hardly registers compared to that calculated by EIO-LCA, see Figure 21.

### *MAETP*

For MAETP both methods deliver qualitatively the same result: hydrogen fluoride is the most contributing factor in this impact category. In addition to the sectors, which play an important role within the other categories ("plastics materials and resins" and "industrial inorganic and organic chemicals"), here the sector "coal" also has significant influence within the EIO-LCA results. For the quantitative result P-LCA calculations provide results below 10% of the EIO-LCA results calculated with the higher price for all four plastics, see Figure 22.

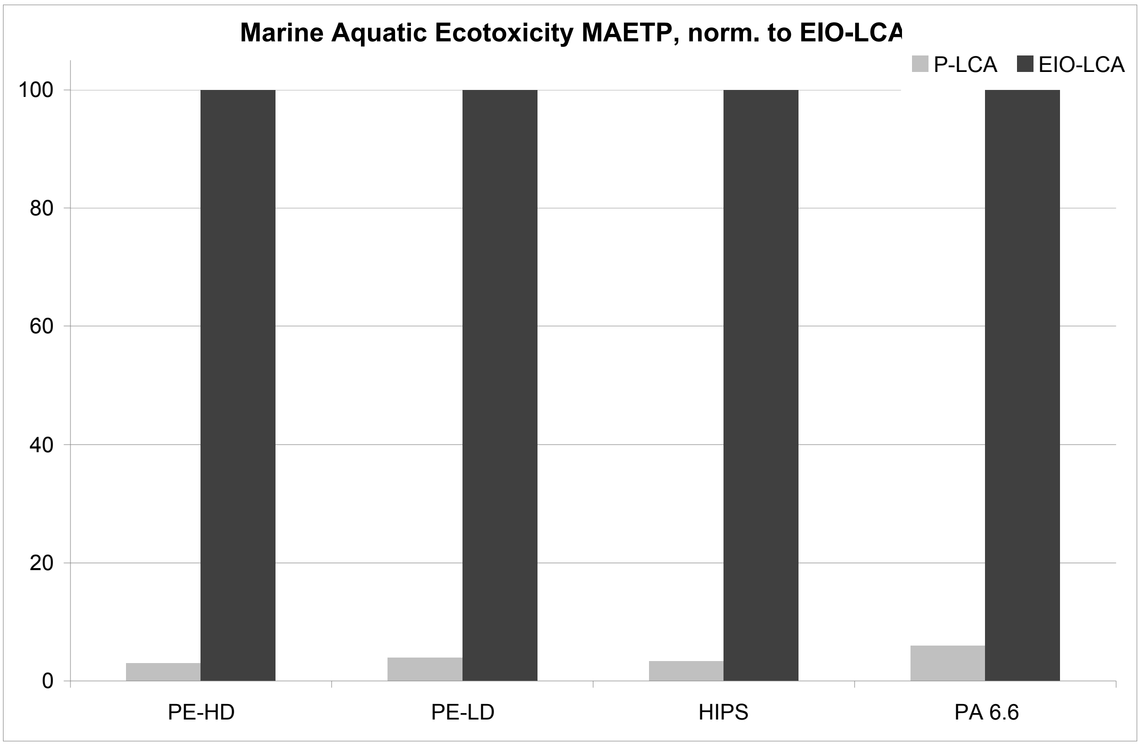


**Figure 22: Results of MAETP, normalised to EIO-LCA (high price)**

### *TETP*

The TETP result of EIO-LCA is mostly dominated by the emission of chromium from "nonferrous metal ore". In the P-LCA results chromium is also the most influential factor for HIPS and PA 6.6, though PE-HD and PE-LD are most influenced by mercury. The quantitative impact of PE-LD and PE-HD within the P-LCA results, however, is insignificant in comparison to the EIO-LCA results. HIPS calculated by P-LCA reaches about 10% in comparison to the EIO-LCA results calculated with the higher price, the PA 6.6 is also well below that, see Figure 23.

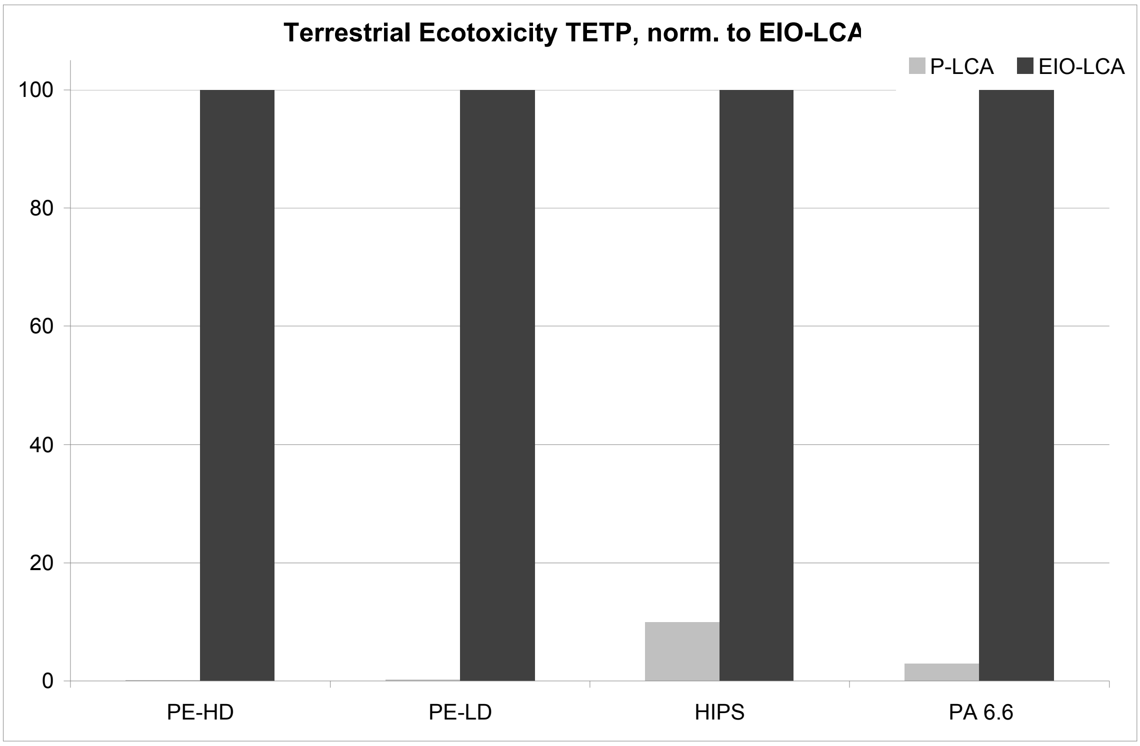


**Figure 23: Results of TETP, normalised to EIO-LCA (high price)**

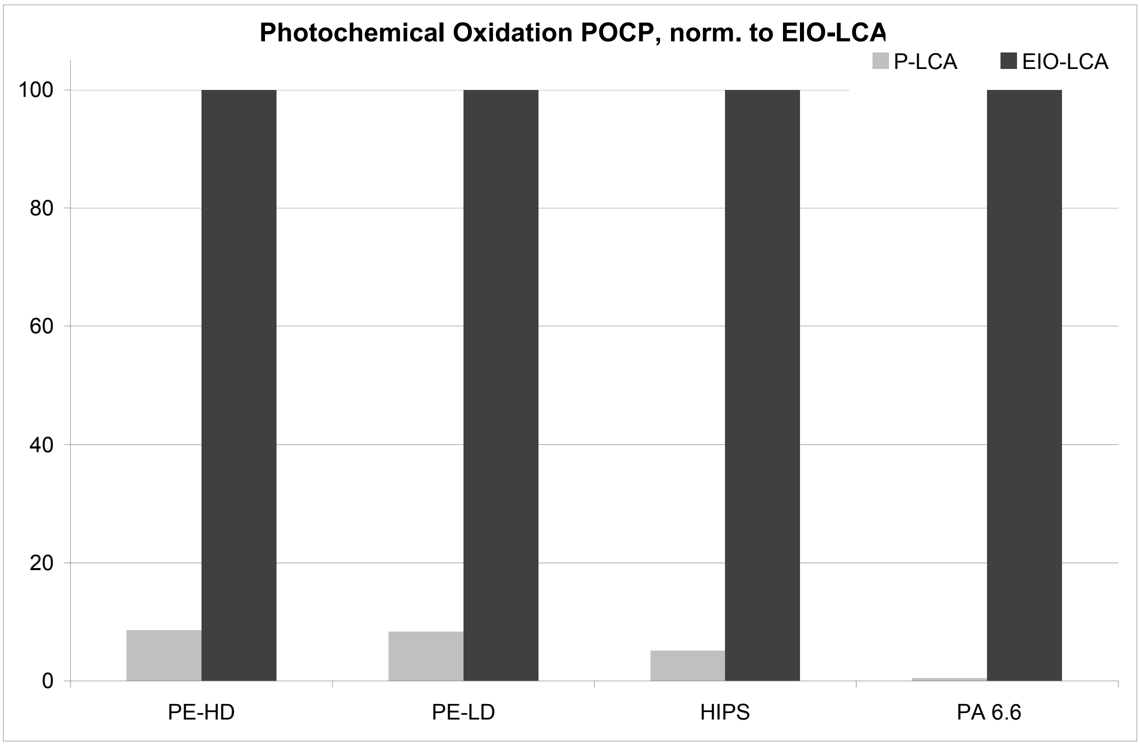


**Figure 24: Results of POCP, normalised to EIO-LCA (high price)**

### *POCP*

NMVOC from (“plastics materials and resins” and “industrial inorganic and organic chemicals” have the greatest impact within POCP for the EIO-LCA results. P-LCA qualitatively delivers the same result for all plastics except PA 6.6 where sulphur dioxide shows a far higher influence. Quantitatively none of the results of P-LCA reach more than 10% of the EIO-LCA results calculated with the higher price in this category, PA 6.6 showing comparatively the lowest impact, see Figure 24.

### *AP*

The AP is clearly dominated by sulphur dioxide and nitrogen dioxide in the results of both methods. Within EIO-LCA there is – in addition to "plastics materials and resins" and "industrial inorganic and organic chemicals" – also a high contribution by "electric services". As for the GWP results the quantitative P-LCA results are comparatively high, reaching between 50 % and more than 75% of the EIO-LCA results calculated with the higher price, see Figure 25.

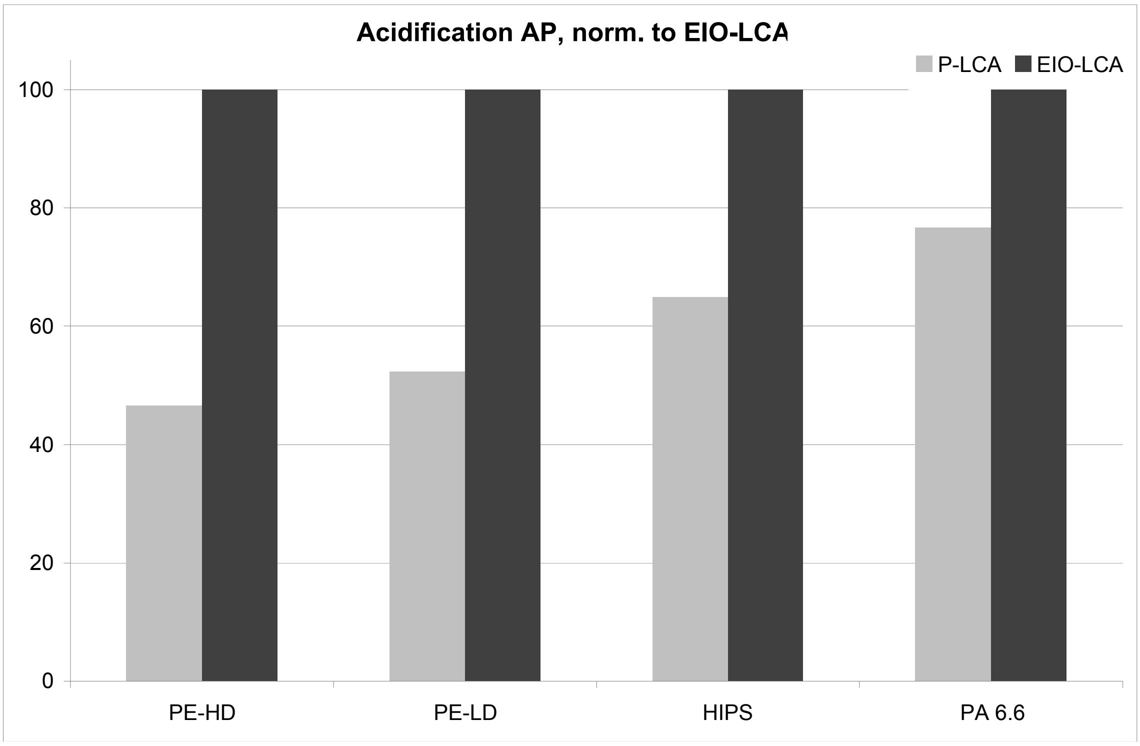


**Figure 25: Results of AP, normalised to EIO-LCA (high price)**

### *EP*

Nitrogen dioxide is mainly responsible for the impact on EP calculated by EIO-LCA (from "plastics materials and resins", "industrial inorganic and organic chemicals" and "electric services") as well as for PE-HD, PE-LD and HIPS calculated by P-LCA. PA 6.6 alone delivers a different result, being influenced most by nitrate and phosphorus with regard to its EP impact, which causes a significantly higher quantitative result than EIO-LCA. The other plastics reach around 40% by P-LCA in comparison to EIO-LCA calculated with the higher price, see Figure 26.

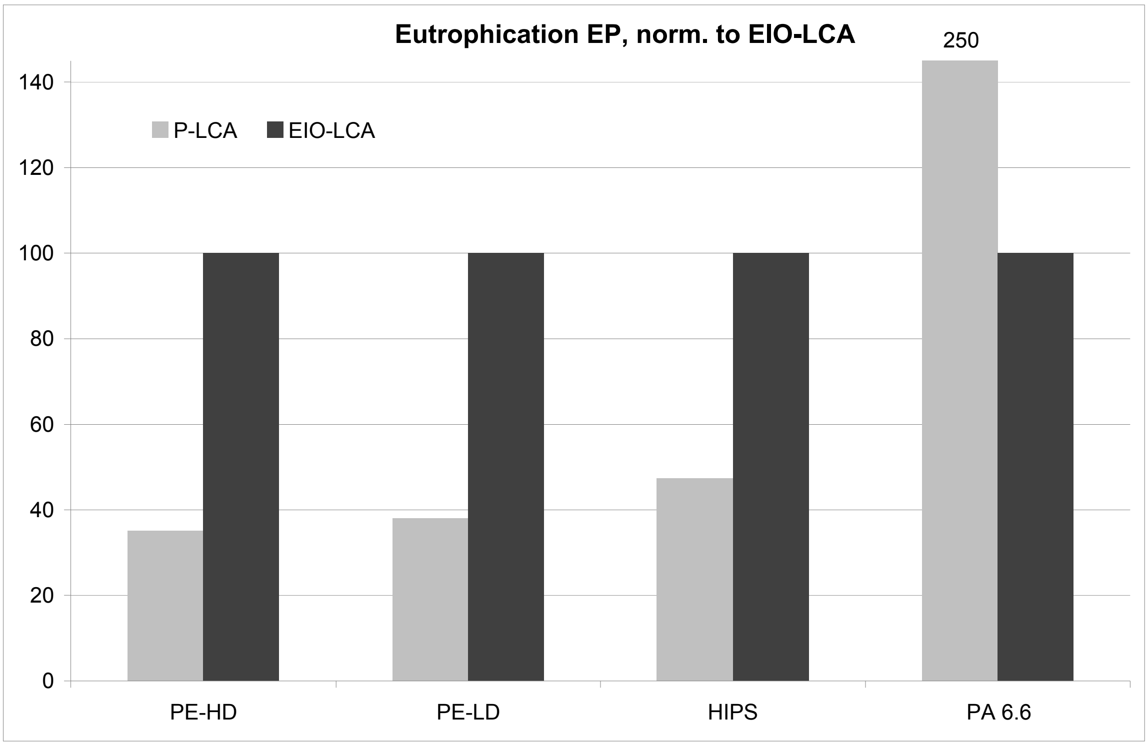


**Figure 26: Results of EP, normalised to EIO-LCA (high price)**

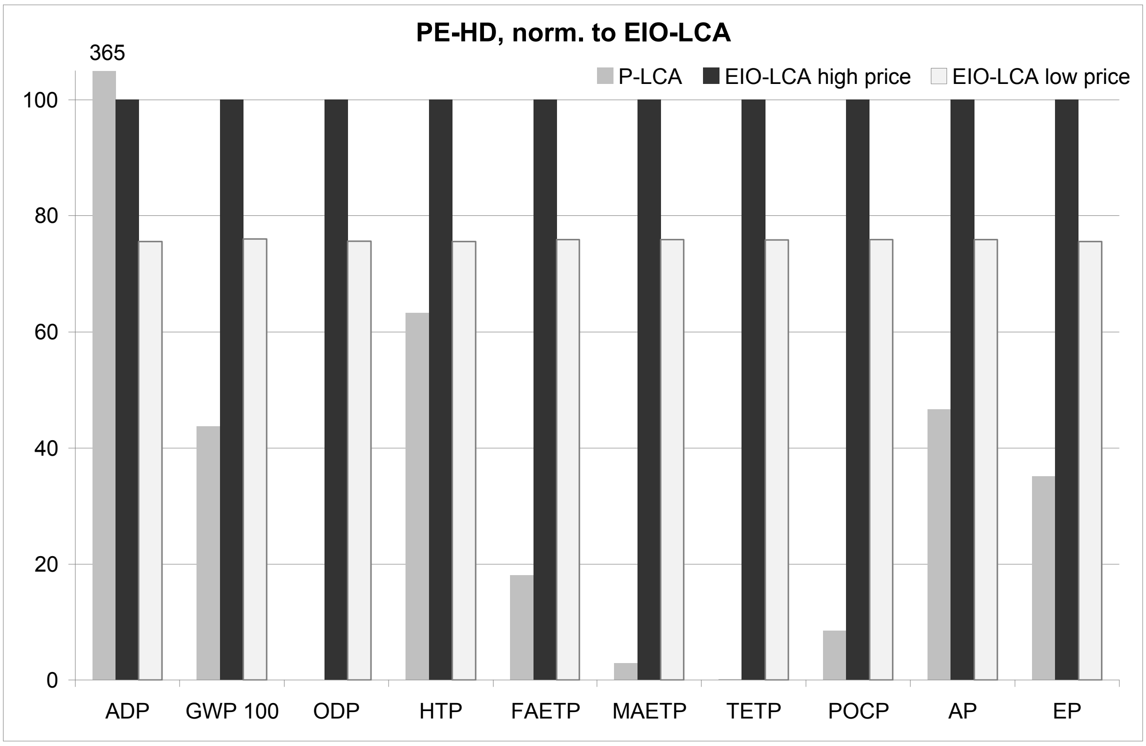


**Figure 27: Results for PE-HD, normalised to EIO-LCA (high price)**

As described above, for EIO-LCA two calculations were conducted using two different price levels. The results of this are shown exemplarily for PE-HD in Figure 27. The price found for PE-HD in April 2009 was 76% of the price found in April 2010, which obviously causes accordingly lower results. However, as the difference in quantitative results between EIO-LCA and P-LCA surpassed this difference largely for all impact categories (except ADP where P-LCA revealed higher results in any case) the overall result is in this case not affected by the price difference.

### 5.3.3 Aluminium composite material

The P-LCA modelling of the aluminium composite material included a comprehensive end-of-life step and therefore two different calculations were carried out, one for the whole life cycle, one including only production and use. The results for these and the results from the EIO-LCA application are shown in Figure 28.

The result follows the ones from the above case studies with regard to ADP, where both P-LCA models reveal higher impacts than the calculation using EIO-LCA, which are dominated by fossil energy extraction within the results of both methods. The quantitative result for P-LCA would be higher than that for EIO-LCA even if only the fossil fuel extractions were considered in both methods, though.

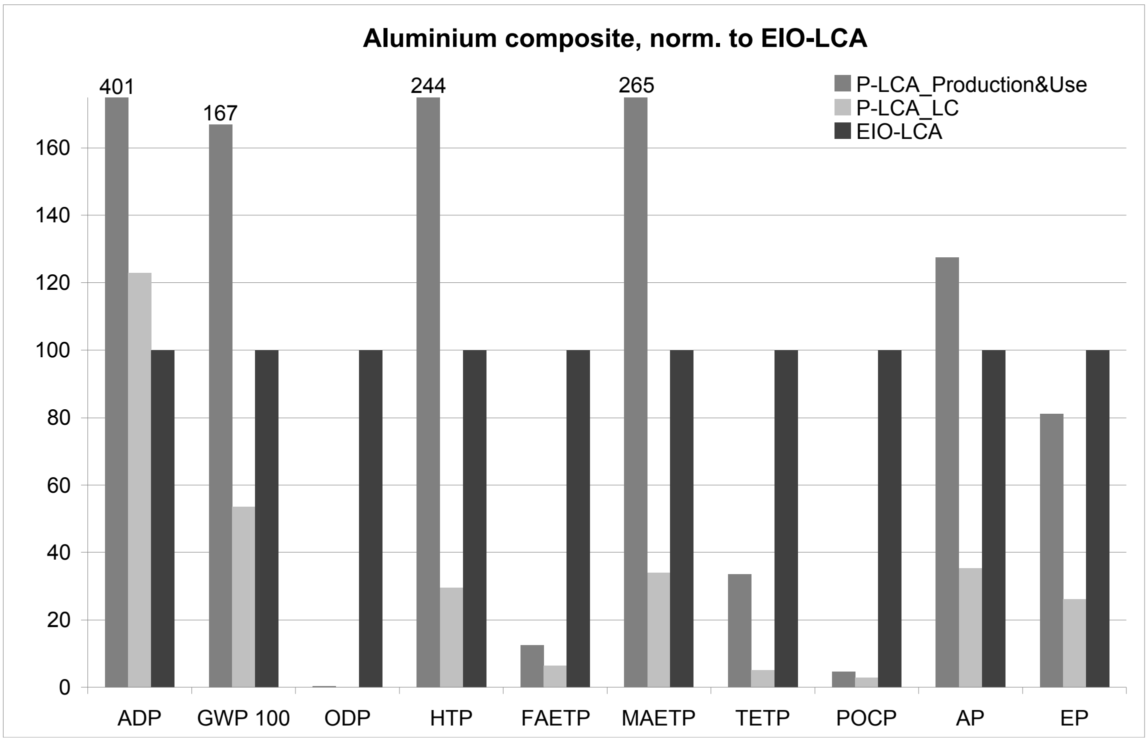


**Figure 28: Results for aluminium composite, normalised to EIO-LCA**

When comparing the calculation of the whole life cycle of the composite by P-LCA with the results for EIO-LCA the results are also similar to those obtained by the other case studies: significantly higher quantitative results by EIO-LCA. However, when taking into account only production and use for the P-LCA calculation the result is more diverse, as described more detailed below for each impact category.

### *GWP*

The GWP result is dominated by emissions of carbon dioxide and R12 in EIO-LCA, with high contributions from the sectors “plastics materials and resins” and “electric services and utilities”. The P-LCA result is also dominated by carbon dioxide, though methane and tetrafluoromethane show high contributions as well. The quantitative result of P-LCA depends highly on the life cycle phases taken into account as the highest impact is caused by the production of the material, but significant credits are given in the end-of-life phase. This leads to a lower impact in comparison with the EIO-LCA result for the whole life cycle and a significantly higher result of P-LCA when only production and use are considered.

### *ODP*

Impacts of both methods on ODP show high contribution by R 11 plus R114 for P-LCA and R12 for EIO-LCA. Aluminium production does not appear to have a great influence here, as the sectors of EIO-LCA contributing most are “plastics materials and resins” and “industrial inorganic an organic chemicals”. However, the quantities of the contributing emissions differ greatly, rendering the ODP calculated by P-LCA insignificant in comparison to the one calculated by EIO-LCA.

### *HTP, MAETP and AP*

For HTP, MAETP and AP the result is similar to the one for the GWP: showing distinctly lower results of P-LCA when the whole life cycle is considered and higher ones when only production and use are taken into account. HTP is most influenced by the emission of hydrogen fluoride from “primary aluminium” and “blast furnaces and steel mills” for EIO-LCA. For P-LCA hydrogen fluoride is also significant but the influence of dioxins is higher. MAETP is dominated by hydrogen fluoride in both methods, for EIO-LCA again originating from “primary aluminium” and “blast furnaces and steel mills”. Sulphur dioxide contributes most to AP in both methods, for EIO-LCA it mainly stems from “primary aluminium” and “electric services.

### *FAETP, TETP, POCP and EP*

FAETP, TETP, POCP and EP show higher quantitative results for the EIO-LCA calculation, independently of considering the whole life cycle or only production and use within P-LCA. The EIO-LCA result for FAETP is dominated by acrolein (mainly from “plastics materials and resins”), which shows no significant influence in the P-LCA results. Here the emissions of vanadium and polycyclic aromatic hydrocarbons (PAH) show the highest contribution. Chromium from nonferrous metal ores contributes most to TETP within EIO-LCA. Chromium also plays a significant role in the P-LCA calculation, though mercury and vanadium both contribute more to TETP. POCP is most influenced by NMVOC from “plastic materials and resins and "industrial inorganic and organic chemicals" within EIO-LCA. P-LCA reveals high contributions from NMVOC, too, but in addition also from sulphur dioxide and nitrogen dioxide. For EP the highest contribution forms nitrogen dioxide in EIO-LCA. The origin of the nitrogen dioxide is diverse, though "electric services (utilities)" have the largest proportion. The result of P-LCA is more influenced by nitrogen oxides.

## 5.4 Summary of the performed case studies

In order to provide additional information on the differences between the two basic life cycle methods evaluated here, P-LCA and EIO-LCA, several case studies were performed in the framework of this thesis. These consisted of studies on copper and plastics materials for macro level applications and a aluminium composite material representing a micro level application. The product systems of theses case studies were described and a comprehensive impact assessment according to the CML method conducted [GUINÉE 2002]. The results of this impact assessment showed significantly higher contributions to most impact categories for the EIO-LCA calculations on the macro level. Exceptions to this could be found for ADP and partly for EP. For the micro level application of a composite material results were similar when the whole life cycle was considered. However, when taking into account only production and use for the P-LCA calculations and disregarding the elaborate end-of-life scenario, results were more diverse, suggesting strong influence of the considered waste management. On the whole results were often similar in quality, meaning that similar emissions contributed to the individual impact categories, but quite different in quantity, meaning the amount of these emissions that were attributed to each considered product.

In the next chapter both the theoretical results described in chapter 4 and the results obtained from the case studies, described in the present chapter, will be discussed.

# 6 Discussion of the Results

## 6.1 Theoretical evaluation

The quantitative results from chapter 4 are used to discuss and compare the suitability of the four life cycle methods for the applications levels, including indications on their general possibilities and inherent limits. The results are represented here as percentage of compliance with the criteria (see also Table 41 and Table 42 on page 71). This was done in order to prevent misleading presentation of the results as the criteria comprise different numbers of sub-criteria (from two to four sub-criteria) and therefore the maximum scores vary.

The results are first discussed for each life cycle methods on its own before they are comparatively discussed for both levels of application.

### 6.1.1 Micro level applications

On the micro level P-LCA shows high compliance with nearly all evaluated criteria (above 80%). Two exceptions to this occur: in the criterion of data availability and accessibility and in the criterion of objectivity. As the possibility for choices when conducting a P-LCA is intentional and a strong point with regard to flexibility this lower compliance with the criterion is method inherent and unlikely to be improved. Data availability and accessibility on the other hand might be improvable through the provision of more region-specific data, though publicly accessible databases containing true micro, i.e. site or company specific data, are less likely to develop significantly due to confidentiality reasons. Particular strong points of P-LCA on the micro level were revealed for method documentation, applicability, scientific soundness and the availability of software tools, see Figure 29 to Figure 31, for which compliance is complete on the micro level.

The only criterion for which EIO-LCA shows full compliance on the micro level is the availability of software tools, for all other criteria the method reaches a maximum of 50 percent in compliance, see Figure 29 to Figure 31. The criteria for which EIO-LCA reaches these 50 percent are applicability, objectivity and data quality. Stakeholder acceptance and scientific soundness appear to be particularly low on the micro level. While several of the EIO-LCA shortcomings seem improvable especially if the method is applied more widely (communicability, stakeholder acceptance or documentation), there are also method inherent features which make it unlikely that EIO-LCA could be generally suitable for micro level applications. Applicability does not seem to be improvable for pure EIO-LCA as it is dependent on method characteristics such as the level of data aggregation which renders it unsuitable for a number of applications for which detailed information on the studied systems is needed. The same is true for its objectivity and scientific soundness as the extent of value choices, e.g. the assumption of proportionality between economic and environmental units or the level on which data is collected and processed, is a basis of the method. For its methodological completeness the picture is not quite as clear even though the current result seems unambiguous. While the fact that the method is not able in its pure form to analyse the whole life cycle is a given, several aspects, e.g. with regard to the definition of system boundary and multifunctional situations can be adapted. On the whole the method is unlikely to become significant for micro level applications.

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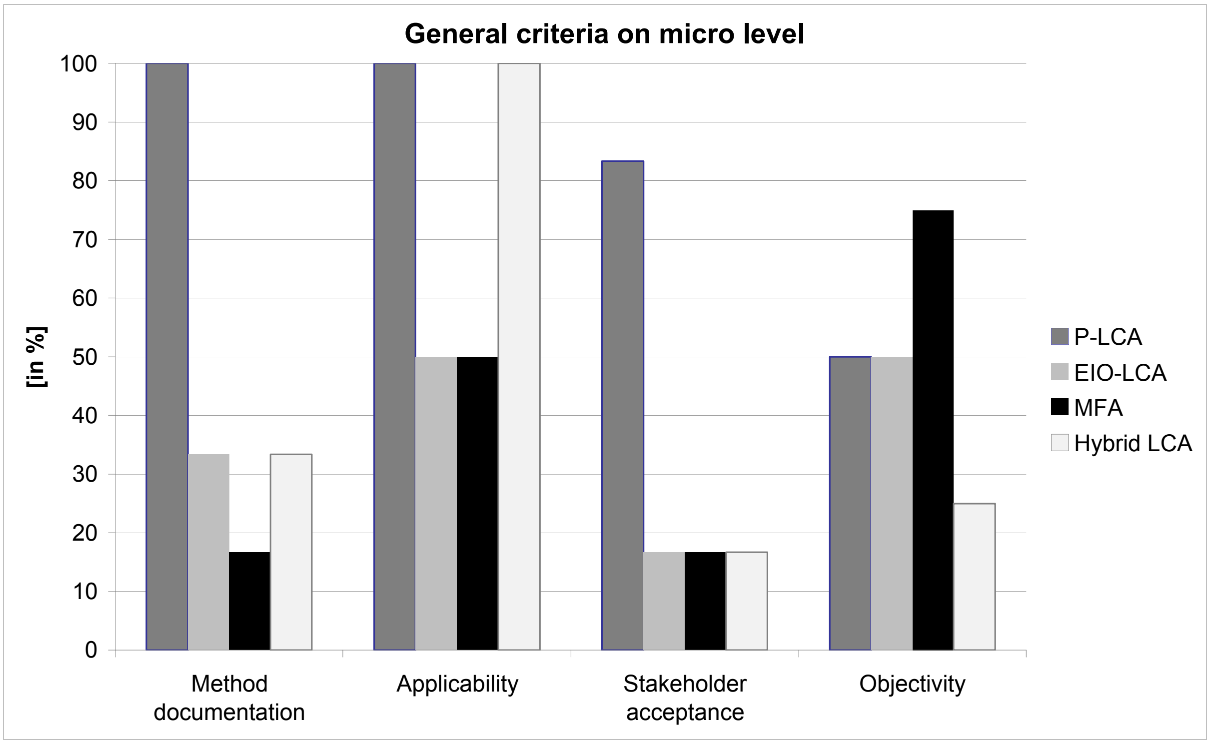


**Figure 29: Results for the general criteria for micro level applications**

MFA only reaches full compliance on the micro level with the criterion of available software tools. However, it shows high compliance (of 75%) in several other criteria, including the already mentioned objectivity, see Figure 29 but also for its scientific soundness and quality of data, see Figure 30. For method documentation and stakeholder acceptance on the other hand the method shows particularly low compliance. As for EIO-LCA there are several current limits on the micro level which could be improved. Communicability could be enhanced if appropriate tools are developed, which would also be likely to influence acceptance. Both criteria might be partly dependent on the documentation of the method and data availability. Applicability on the other hand touches the inherent setup and intention of the method as does its methodological completeness especially with regard to the possibility of a comprehensive environmental assessment. The MFA method will not be adapted to include an environmental assessment though it might still serve as the basis for one.

Hybrid LCA reaches full compliance on the micro level only for applicability but shows high compliance (more than 80%) for data quality, too, see Figure 29 and Figure 30. On the other hand compliance is particularly low for stakeholder acceptance and communicability of the method. These two criteria can be accounted to the fact that the method has not been used in practice and is still under development. If method documentation improves and data availability was increased the practical importance of Hybrid could increase. If such practical applications occur in future these shortcoming might be remedied. Unlike for the pure EIO-LCA the limited objectivity in the method is not necessarily inherent as the low scoring was based on insufficiencies in the current methodology. On the whole the method has the potential to combine P-LCA and EIO-LCA as was intended with its development but the current situation does not allow for that yet.

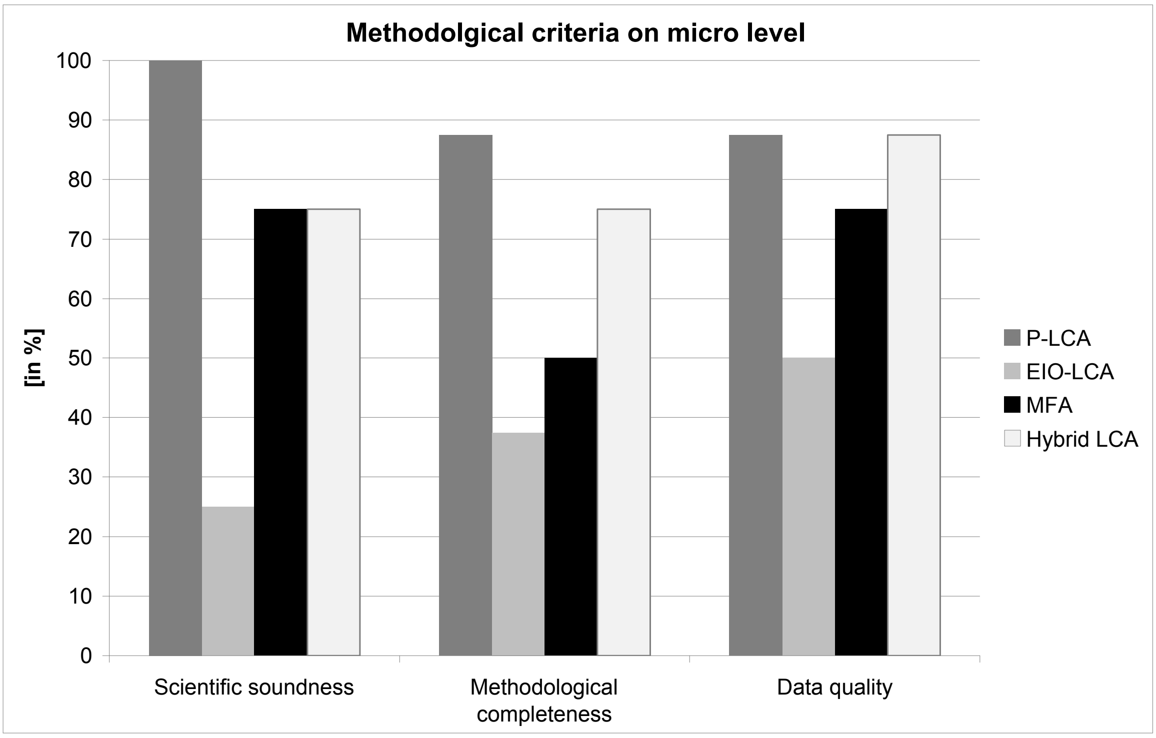


**Figure 30: Results for the methodological criteria for micro level applications**

Comparing the individual results of the methods is becomes evident that P-LCA shows significant advantages over the other methods for its documentation, its acceptance and communicability. This is in line with the fact that P-LCA has been applied widely and is being targeted by numerous national and international bodies for its specification and improvements in applicability. All three criteria, however, refer to issues which are not method inherent. For the two data criteria (quality and availability) as well as the availability of software tools the differences between the methods are less significant. The criterion of objectivity is the only one of all criteria on the micro level where the results of P-LCA are surpassed by those of another method: MFA was found to have higher compliance with the evaluated aspects and sub-criteria, namely due to the influence of assumptions, see Figure 29. Taking these findings into account leads to the assessment that from a methodological point of view P-LCA is most advantageous in terms of scientific soundness and methodological completeness.

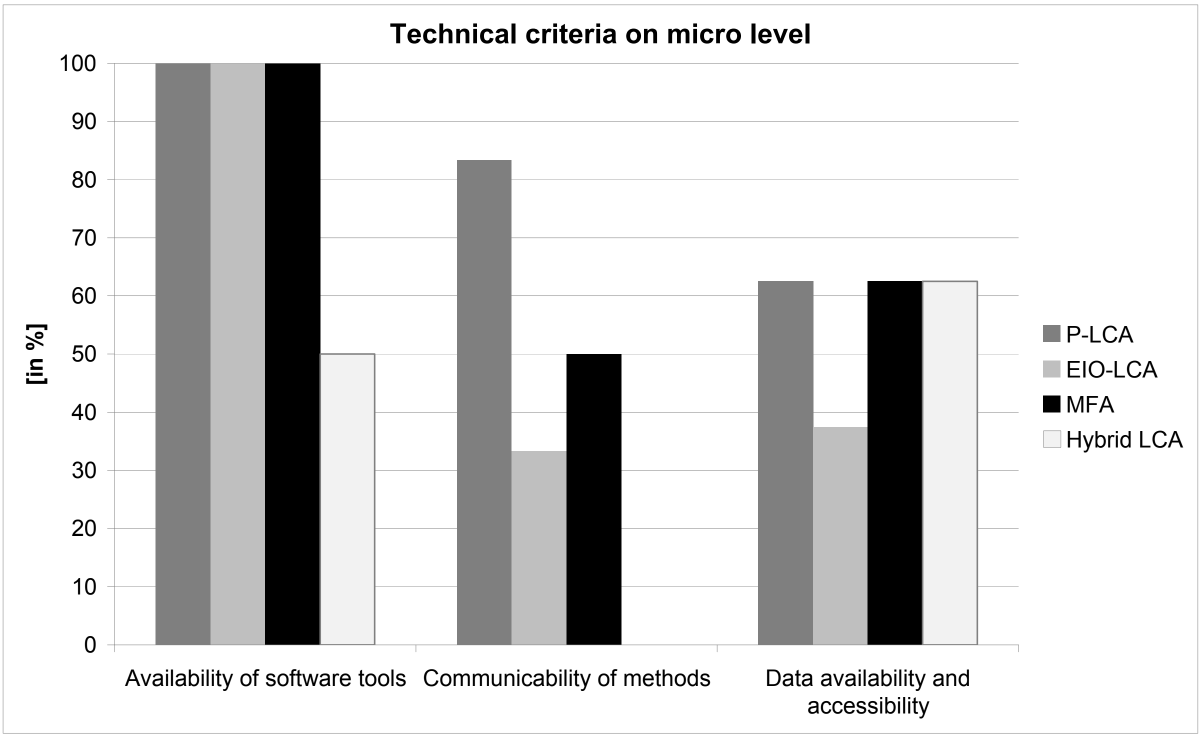


**Figure 31: Results for the technical criteria for micro level applications**

### 6.1.2 Macro level applications

P-LCA achieves full compliance only for the availability of software tools for which the score is unaffected by the application level for all methods. P-LCA also still shows high compliance (more than 70 %) for applicability, data quality and data availability. Scientific soundness and methodological completeness, which were noted to be particularly positive methodological features on the micro level, are decidedly lower, see Figure 33. Evaluated aspects within these criteria refer to inherent characteristics of the method and are therefore unlikely to be improvable. As P-LCA has not been as widely applied on the macro level as on the macro level, communicability and stakeholder acceptance also show lower compliance, see Figure 32 and Figure 34. However, these shortcomings could be improved if the method is applied more on the macro level, also necessitating better method description for this level which is currently insufficient. Even though stakeholder acceptance is lower than on the micro level is still highest of all considered methods which can be accounted for by the fact that even though the number of applications is lower than on the micro level, it is still applied by different user groups. Objectivity is not affected by the level of application and remains to be of medium compliance due to the flexibility with regard to assumptions.

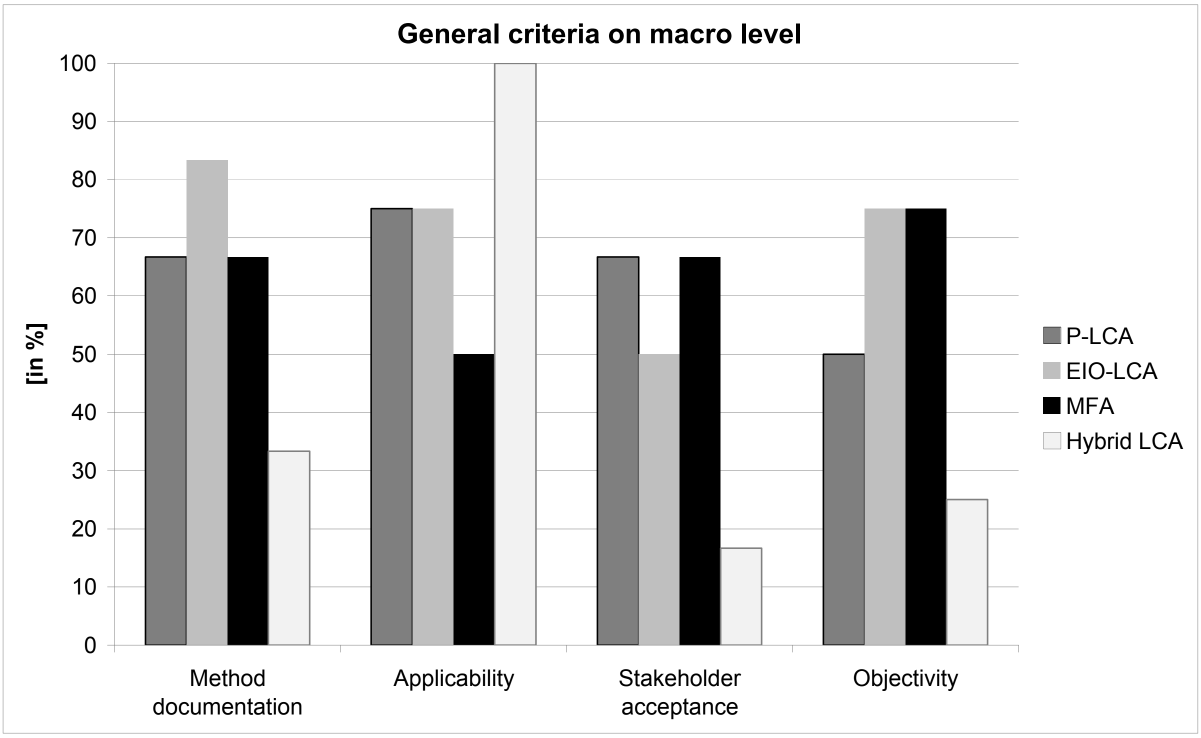


**Figure 32: Results for the general criteria for macro level applications**

EIO-LCA also shows full compliance only with the criterion on software tools on the macro level just as it does on the micro level, though also shows high compliancy (over 70%) for its documentation, applicability, objectivity and data quality. Even for those criteria where compliance is lower (up to 70%) the increase in comparison to the micro level is notable, see Figure 32 to Figure 34. The magnitude in increase differs; it is highest for the criterion on method documentation, which is best of all considered methods. The general increase in compliance is accounted for one by greater application on the macro level, which leads to higher compliance with those criteria that are affected by previous application such as stakeholder acceptance. A second reason for the general increase is the underlying focus of the method on the macro level, which enhances applicability and communicability. The criteria evaluating methodological issues like objectivity and methodological completeness increase due to this as well. The methods strong point in comparison with the other considered methods lies – apart from the on concerning its documentation – in its objectivity. With regard to data availability, however, it scores lowest of all methods, the reason for which can be found in the dependency on data for which availability cannot be influenced by the LCA practitioner and its inherent incompleteness with regard to the coverage of the whole life cycle. Scientific soundness suffers from the same shortcomings as on the micro level: the uncertainty in the assumption of the proportional link between economic data and related environmental impacts but increases at the same time as the level of data and results is more consistent.

MFA shows full compliance with several criteria: scientific soundness, data quality, communicability and – as on the micro level – the availability of software tools, see Figure 33 and Figure 34. In addition, objectivity, methodological completeness and data availability achieve high compliance (over 70%) and MFA appears to be most compliant of all considered methods for the criteria of scientific soundness and communicability. Together with stakeholder acceptance the latter shows the highest increase of all criteria in comparison with the micro level, which is explained by the wider use of MFA on the macro level though stakeholder acceptance still only reaches a 50% compliance due to aspects concerning the inclusion of stakeholders. Method documentation also increases by the same magnitude. However, even though MFA shows an overall strong compliance with the evaluated criteria there are some aspects, which will restrict its suitability. These are concerned with the applicability of the method, which does not change in comparison to the micro level as the range of tasks, which may be accomplished, does not differ, see Figure 32.

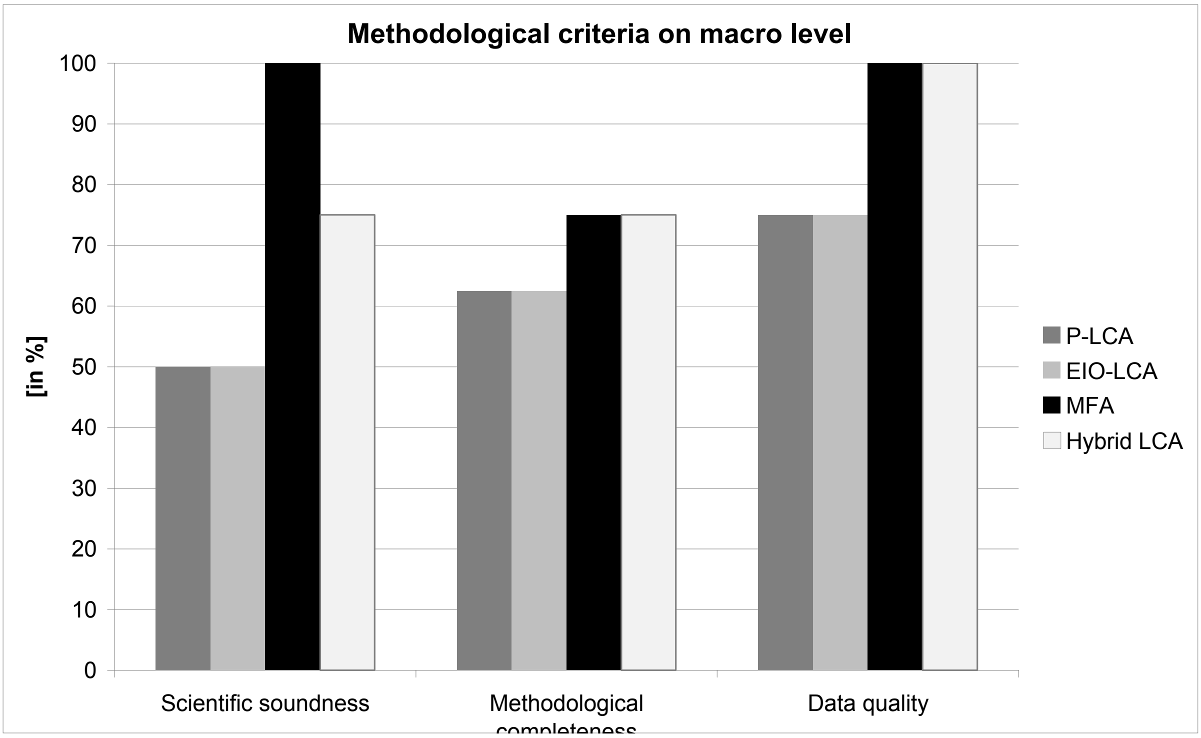


**Figure 33: Results for the methodological criteria for macro level applications**

As on the micro level Hybrid LCA shows full compliance with the applicability to a wide range of tasks. In addition compliance with data quality is complete and high for data availability, which can be accounted for by the effects of the combining features from P-LCA and EIO-LCA. It also reveals compliance of over 70% for its scientific soundness as it does on the micro level. Apart from these criteria the suitability of Hybrid LCA does not show differences in comparison with the micro level. Criteria relating to previous applications change as none exist on the macro level; neither is there a more comprehensive description of the method. The overall unchanged suitability is to be expected if it is assumed that Hybrid LCA manages to integrate P-LCA and EIO-LCA parts beneficially as each of the methods as different strengths on the two application levels.

Considering these finding for the individual methods shows that for the evaluation of method applicability on the macro level results are distinctly more widespread and no method appears to be predominantly advantageous. On the whole MFA appears to show the best suitability for the macro level, though with the stated limitations in applicability. P-LCA and EIO-LCA seem equally well suited, though with different foci and strengths. Both criteria in which P-LCA reaches better compliance than EIO-LCA relate to actual applications (data and acceptance) and are not method inherent. These are therefore issues in which EIO-LCA might improve while the compliance of P-LCA with the aspects of objectivity (where EIO-LCA shows higher compliance) cannot be changed without changing underlying principles of P-LCA. Hybrid LCA on the other hand shows valuable potential as it does on the micro level but reveals currently too many limitations to be practically relevant.

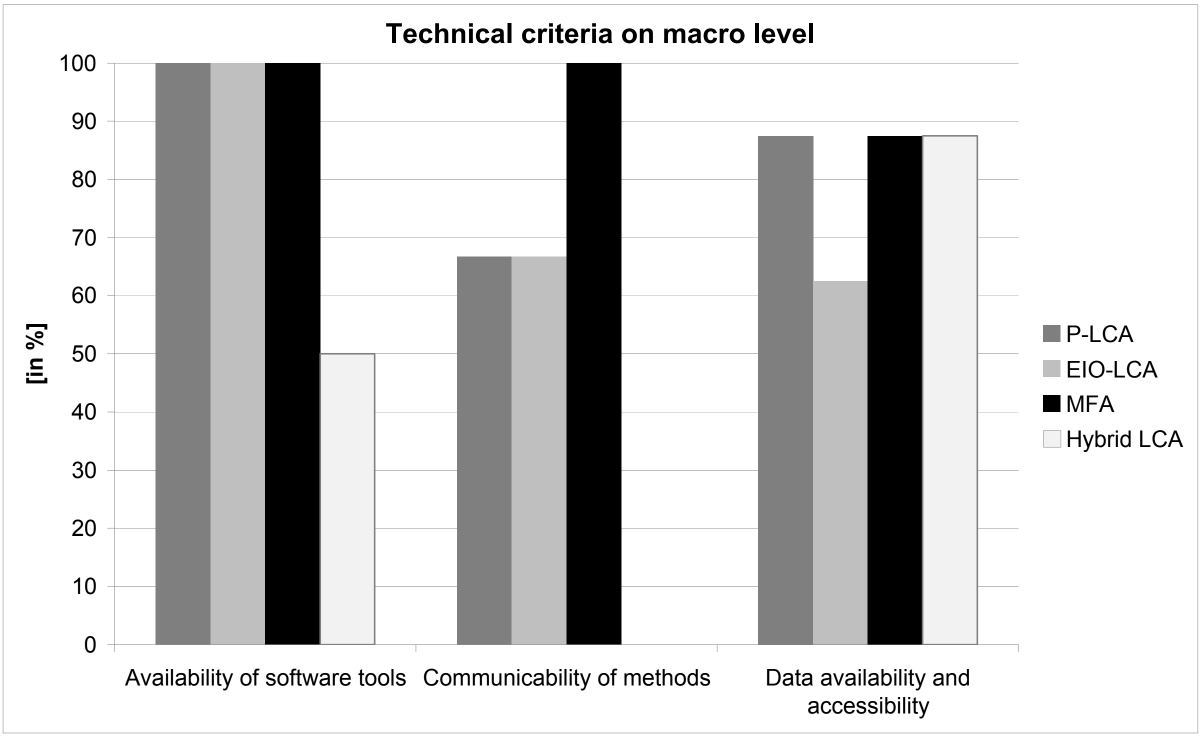


**Figure 34: Results for technical criteria for macro level applications**

## 6.2 Cross-check with the case-studies

The case studies were performed in order to verify the practical stability of the theoretical evaluation. It will therefore be checked for all evaluation criteria if they can be confirmed or refuted by the case studies and where the general evaluation might differ in specific cases. Some of the criteria are not case dependent at all, which will be stated below. Obviously the verification will only be performed for P-LCA and EIO-LCA.

### 6.2.1 General criteria

The criterion on method documentation is not influenced by the case studies as the criterion aims at a description of the method itself.

The criterion on applicability is linked to practical considerations. For P-LCA complete compliance was evaluated for the applicability to a wide range of goods and services on both levels and to a broad range of tasks on the micro level. For the macro level limitations are stated with regard to the applicability to a wide range of tasks due to e.g. cause-effect chains which may not be apparent.  These findings are confirmed by the case studies. The case studies cover different stages in the value chain which were assessed and were also flexible to e.g. the impact assessment. However, for the range of possible tasks it is found that the necessary aggregation of data on the macro level disables the identification of cause-effect chains as well as hot spots along the life cycle. The assessment of only partial fulfilment with the sub-criterion on the macro level is therefore justified. On the micro level such limitation are not apparent as a more detailed analysis of the underlying information is possible.

For EIO-LCA compliance was evaluated as partially fulfilled the applicability to a broad range of goods and services on both levels and to a broad range of tasks on the micro level, while compliance was evaluated complete for the applicability to a broad range of tasks on the macro level. Though it is established that for the case studies not only the production phase was included (due to adaptations in the IO model) there is a strong focus on this phase. Information on use or end-of-life phase is basic and e.g. waste management could not be assessed in detail. The applicability to different tasks on the micro level cannot be assessed with certainty as only one case study was conducted on that level. On the macro level, however, the original evaluation is challenged by the findings of the case studies. Though some of the considered aspects are confirmed, such as the identification of drivers and cause-effect chains, others are refuted. The possibility of the comparison of systems depends on the systems in question. For the study on different plastics materials, which are all located in one sector and therefore environmental results are decided by price differences only, their detailed comparison and improvement analyses are not possible without further disaggregation of the sector (which would lead to a Hybrid LCA model). Therefore the complete compliance assigned in the theoretical evaluation is disputed here.

The criterion on stakeholder acceptance is not dependent on individual case studies.

The criterion on objectivity was evaluated as partially compliant for P-LCA in both sub-criteria and on both levels. EIO-LCA was assigned full compliance for reproducibility on both levels, no compliance for the influence of assumption on the micro level and partial compliance on the macro level. For P-LCA the estimated reduction in reproducibility if assumptions are change is not dispute in general. However, for the macro level case studies flexibility was lower than generally assumed which means that with the aspects taken into consideration here the results would be reproducible in these specific cases. The evaluation of the sub-criterion influence of assumptions is backed. Though on the macro level the extent of value choices the practitioner can apply is low, value choices are still inherent and have been made on a different level (e.g. with the choices in compiling the database). They are, however, stated. The partial compliance is further justified because the influence of these assumptions cannot be quantified on either scope level. For EIO-LCA there is no indication by the case studies that the scoring awarded for reproducibility or influence of assumptions on is incorrect. As evaluated before value choices are clearly stated in the documentation, but it is not possible to quantify the magnitude of their impact.

### 6.2.2 Methodological criteria

The sub-criteria defining scientific soundness were evaluated complete on the micro level and partially compliant on the macro level for P-LCA. Rating was also partially compliant on the macro level for EIO-LCA, partially compliant for validation/verification checks and not compliant for the plausibility of results on the micro level. For P-LCA this evaluation appears to be sound for those parts that are affected by the case studies, i.e. peer reviews were conducted for the data used on the macro level and the results of the micro level application, verification checks have been performed and recognisability of errors can be assumed. The only limitation occurs for the possibility of results against environmental measurements on the macro level, which is not possible for the case studies without further information from the data sources and cannot be conducted by the practitioners themselves, as was already evaluated on a general level. For the sub-criterion plausibility of results no difference between the general rating and the findings of the case studies can be detected. For EIO-LCA, too, no difference is discernable from the findings of the case studies. Limitations of the general evaluation, such as with regard to the disaggregation of environmental data or the consistency of the data for micro level applications, still apply.

The criterion on methodological completeness takes into account for sub-criteria: method definition with regard to system boundary and multifunctional situations, the methods' suitability for comprehensive environmental assessment and the enabling of the analysis of the whole life cycle. The first two and the last are not dependent on case studies, but if they are conveyed from the purely methodological level to the database level, some additional statements can be derived from them. It was evaluated on the general level that P-LCA does not comply with the aspects for the definition of system boundaries on the macro level. Due to the application of predefined data, however, the boundaries including applied cut-off criteria were also predefined. If this finding can be generalised for all macro level application of P-LCA cannot be estimated here. The same is true for the enabling the analysis of the whole life cycle by EIO-LCA which is allowed for by the specific setting of the database. The suitability for a comprehensive environmental assessment can be checked in more detail as an impact assessment was carried out for both methods and the results closely compared. Implications from this are therefore given below in chapter 6.2.4

Data quality is defined by data characteristics, representativeness, the availability of independent review and data documentation. All four sub-criteria can be checked for the data used in the case studies. On the micro level P-LCA was evaluated to show complete compliance with the first three of the sub-criteria and partial compliance with data documentation. On the macro level compliance was evaluated complete for independent reviews and documentation. Partial compliance was evaluated for data characteristics and representativeness. EIO-LCA was evaluated to show complete compliance with the sub-criterion of independent reviews on both levels and data representativeness on the macro level. Data characteristics were evaluated to be not compliant on the micro level; all other sub-criteria were evaluated to be partially compliant with the considered aspects on both levels. For P-LCA the scoring appears to be sound on the micro level as data characteristics are consistent with the level of application, data is representativeness and review of data has occurred, though the documentation is not entirely transparent due to confidentiality reasons. On the macro level the restriction within data characteristics and data representativeness, e.g. with regard to data updates or the time lag between data collection and provision, apply. The full compliance with the sub-criteria of independent reviews and data documentation also seem justified by what information is provided on the database. For the EIO-LCA the evaluation is backed by the case studies for limitations in the data characteristics on both levels and representativeness on the micro level, as is the compliance with reviews on both levels and representativeness on the macro level. However, the documentation of the data is transparent and comprehensive and the evaluation of this sub-criterion would therefore be improved in this specific case on both levels.

### 6.2.3 Technical criteria

The criterion for the availability of software tools is not affected by the conduction of case studies. It shall be noted, however, that the EIO-LCA studies were carried out with a free, expert tool (which could also be used for P-LCA) and the P-LCA studies were carried out with a commercial expert tools, backing the evaluated diversity in models.

The criterion for the communicability of the methods was evaluated through the sub-criteria of clarity of the method, their comprehensible calculation and transparency and the availability of established communication. The latter is not case dependent, the first two are checked. Clarity of the methods was evaluated partially fulfilled for both methods, with the exception of full compliance for EIO-LCA on the macro level. Limitations were based on the unambiguousness of the P-LCA results and undefined extrapolation of data to the macro level. For EIO-LCA limitations were based on a lack of comprehensibility between IO tables and environmental impacts. The P-LCA evaluation is not disputed by the findings of the case studies. For EIO-LCA comprehensibility of the links between IO and environmental information is improved due to comprehensive documentation in this case. However, due to the applied comprehensive environmental impact assessment applied here, unambiguousness was introduced into the EIO-LCA results as well. The sub-criterion of comprehensible calculation and transparency was evaluated fully compliant for P-LCA on the micro level and partially compliant on the macro level; the evaluation for EIO-LCA was vice versa. In accordance with the general evaluation it can be said that the basic data for P-LCA is indeed accessible on the micro level but its aggregation to macro level data is not documented in detail. The EIO-LCA evaluation also appears to be in accordance as data is highly aggregated for the macro level through documented calculations but basic data no longer accessible.

For the evaluation of data availability and accessibility it was taken into account if data covers the whole life cycle, is available for different regions and for all relevant impact categories and also if it is available publicly at an affordable cost. P-LCA was evaluated fully compliant with life cycle coverage and availability of data for impact categories on both levels, partially compliant with availability of data for different regions on both levels, non compliant with the availability of databases on the micro level and fully compliant with their availability on the macro level. Availability of databases was evaluated for EIO-LCA the same as for P-LCA and partially compliant for the other sub-criteria on both scope levels. The sub-criterion of data availability for different regions is not highly important here, as the case studies were carried out for a specific region for which data existed. The evaluation of P-LCA is also quite straightforward as there are no issues with coverage of all life cycle stages or impact categories, databases with true micro level data do not exist, but freely accessible macro data was used. The database used for the EIO-LCA studies is not free but still rated as to come under the definition of "affordable". However, the evaluation of EIO-LCA for life cycle and impact category coverage could not be backed by the case studies as in contrast to the general evaluation the whole life cycle was taken into account as was the same comprehensive set of impact categories as for the P-LCA application.

### 6.2.4 Discussion of the environmental impact assessment

Within the case studies a comprehensive environmental impact assessment was carried out for both P-LCA and EIO-LCA, which delivered significantly different results on a quantitative scale. As there is no possibility to measure the correctness of either of these quantitative results, qualitative observations are discussed here.

Despite of the quantitative differences it is notable that the emissions mainly causing impacts in the respective impact categories are often the same in both methods so that qualitatively the emissions associated with individual products appear matched. Notable differences only occur in the impact categories of Human Toxicity and Freshwater Aquatic Ecotoxicity.

The generally higher result of P-LCA in the category of Abiotic depletion was attributed to the fact that in the EIO-LCA model only fossil fuel extraction is included. However, even if the ADP contributions originating from other sources are deducted from the P-LCA result, the calculated ADP is still higher than the one calculated by EIO-LCA.

The results of P-LCA within the categories of Freshwater Aquatic Ecotoxicity, Photo-Oxidant Formation and Ozone Layer Depletion are the lowest when compared to the EIO-LCA results. In the case of FAETP the impact is caused mainly by the emission of acrolein within the EIO-LCA model, a substance which does not play a significant role within the P-LCA data but shows high impact potential. Acrolein also may not be as influential for all plastics materials as the EIO-LCA results suggest to the generalisation of plastics into one sector. While via acrylonitrile it is a part of PA 6.6 production such a strong connection is not apparent for the production of the other considered plastics materials (see datasheets of the respective plastics materials on [JRC-IES 2009]). Nevertheless, the effect of acrolein is counterbalanced only for the result of PE-HD where dioxins have a strong influence. Dioxin appears to be represented less in the EIO-LCA data than in the P-LCA data as it can be noted that P-LCA results are relatively higher (in comparison to the EIO-LCA result) for those materials for which a significant dioxin emission is assigned than for those materials without it. The low result of POCP and ODP for P-LCA might be caused by the sector of "industrial inorganic and organic chemicals" within the EIO-LCA model, as these are the only two categories where the sector has a strong influence, independently of the case study. Possibly the time frame of the employed data may be of influence here as the data used for EIO-LCA originates from 1990 since when improvements with regard to these environmental impact categories have occurred.

It is often assumed that EIO-LCA is better suited to reveal emissions caused by service sectors than P-LCA. In the case of the applications undertaken here, there is one service sector, the sector called "electric services (utilities)" which is found to contribute highly to several EIO-LCA results. However, the impact categories for which this is the case, Global Warming, Acidification and Eutrophication, are those categories for which the P-LCA result is relatively high (in comparison to the results in the other categories).

From the results of the copper sheet no reasons for the differences within the results of the two methods can be deduced in addition to those stated above on a general level.

The case study on the aluminium composite material showed that for a comprehensively modelled micro level application the end-of-life phase can have a high impact on the overall results due to credits given but that this impact cannot be modelled by EIO-LCA and the basic recycling sectors the used model contains.

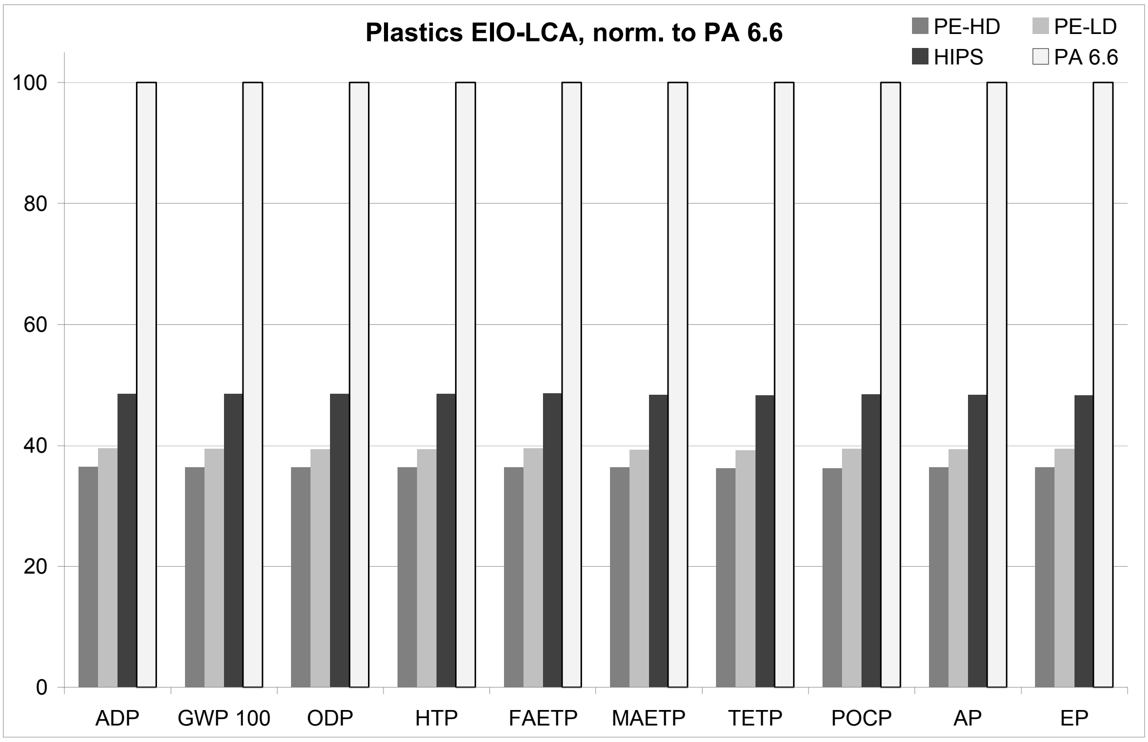


**Figure 35: Results of EIO-LCA for the plastic materials, normalised to PA 6.6**

The case study on the plastic materials was conducted to account for differences or similarities between the methods when a system comparison is intended that involves several products originating from one IO sector. Therefore, when applying EIO-LCA to different plastics materials the differences in the result will be strictly proportional to price differences, as shown in Figure 35.

The result obtained by P-LCA showed a differentiation, which is not entirely dependent on the (price) value of a material, see Figure 36. For the categories of Global Warming, Marine Aquatic Ecotoxicity, Acidification and Eutrophication P-LCA showed the same relative ranking of the materials as EIO-LCA but for all other impact categories at least one material showed higher impacts than a more expensive one. This is most notable in the case of PE-HD as the least expensive material, which nevertheless causes higher impacts than PA 6.6 and/or HIPS in several impact categories. Though four plastics materials are not sufficient for a statistical analysis to substantiate this trend, other work has been conducted showing similar results. BERGER & FINKBEINER (2010) showed that proportionality between Primary Energy Demand (which was taken as a basis for the selection of plastics materials here and corresponded with their price value) and other impact categories is not necessarily evident [BERGER AND FINKBEINER 2010]. With EIO-LCA on the other hand the proportional distribution is inherent in the system and will not differ when assessing more plastics. The only possible way to remedy this would be through disaggregation of the sector containing plastic production and thereby a hybrid approach.

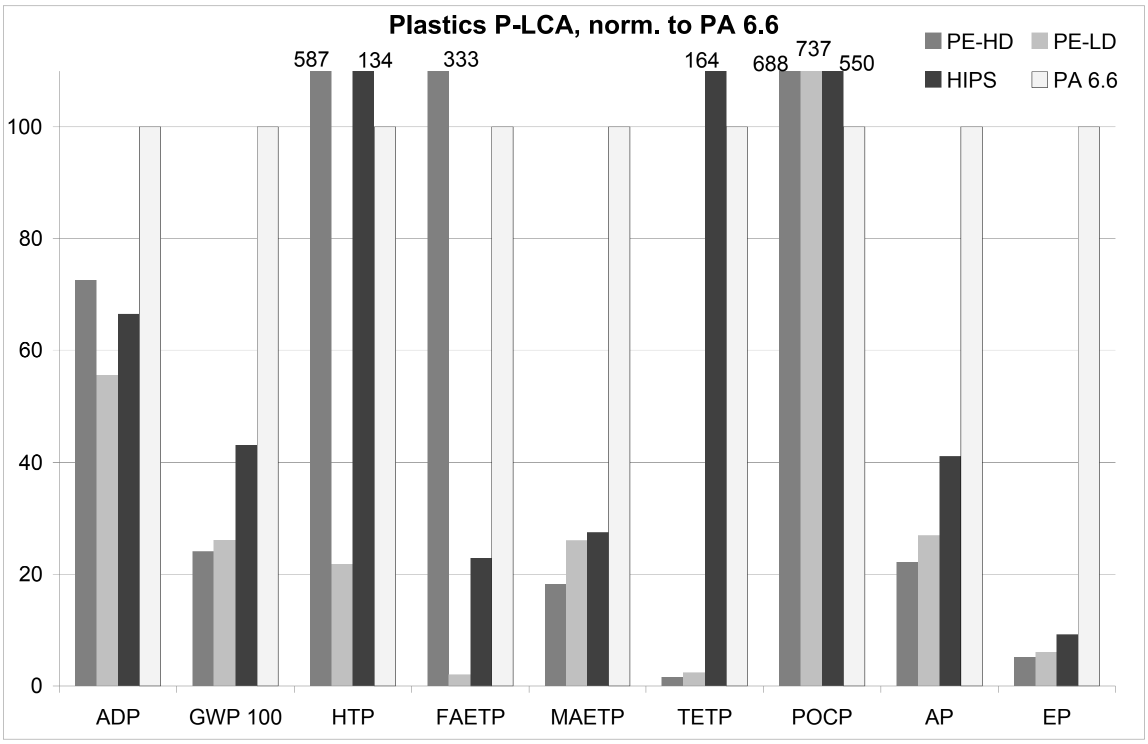


**Figure 36: Results of P-LCA for the plastic materials, normalised to PA 6.6**

# 7 Conclusions and Outlook

The overall objective of the study was to evaluate the selected life cycle methods for their theoretical suitability on micro and macro level decision-making application and to cross-check this theoretical suitability with the application of case studies.

The evaluation undertaken here assigns quantified values based on verbal justification on a three-tiered scale. It may be argued that this scale is too narrow to differentiate sufficiently between the methods. However, the conducted case studies confirmed the results at least for EIO-LCA and P-LCA. In addition, the five-tiered scale applied in the EVALCA project revealed only slightly different results, in some cases favouring one method in others another one [REIMANN ET AL. 2010], but not changing the overall results. Furthermore the assignment of quantified values based on verbal justifications may not be unambiguous in itself. To limit subjective influence the expertise of experts on the evaluated methods was called upon for the development of the evaluation scheme and the evaluation itself.

On the micro level the results obtained from this study are unambiguous: P-LCA shows suitability for the considered evaluation criteria which is higher or at least equal to that of the other methods in all but one case (MFA receiving the highest score for its objectivity) and shows generally high compliance with all criteria. The lower estimated suitability for Hybrid LCA is caused by criteria, which are not inherently method dependent but are also based on the current situation. It can therefore be deduced that the suitability of Hybrid LCA for micro level application can be improved. The same is true for MFA, though its applicability will remain limited as the method is not designed for a comprehensive environmental assessment, though it can serve as the basis for one. EIO-LCA shows least suitability on the micro level, most notably including shortcomings in method inherent criteria, which render it unlikely that the method could become significantly more suitable on the micro level. The case study performed for EIO-LCA and P-LCA confirms these finding even though it was stated that EIO-LCA might be evaluated with higher compliance in three criteria: data quality and availability and methodological completeness. However, EIO-LCA shows a maximum of 50% compliance in these criteria so that changes, which affected only one of the sub-criteria, will not change the overall result. For P-LCA the case study revealed no likely differences in the compliance.

On the macro level the result is diverse. Overall MFAs suitability seems highest though with the same limitations regarding applicability as on the micro level. Its compliance with scientific soundness, data quality and objectivity appears to be particularly good. Hybrid LCA shows a high potential for macro level application, though the revealed shortcomings would need to be solved before it might become practically relevant. P-LCA and EIO-LCA reveal differences in specific criteria due to their different foci though not in their overall suitability. The results obtained from the case studies performed for the macro level show a higher potential effect on the evaluation than on the micro level. P-LCA was evaluated as having limitations in objectivity and methodological completeness, which were revealed less relevant in the specific case studies. In the case of objectivity a different scoring in one of the sub-criteria would not cause the result to change significantly, as the compliance of P-LCA in this criterion is considerably lower than that of EIO-LCA and MFA and considerably higher than that of Hybrid LCA. In the case of methodological completeness, however, differences between the methods are lower so – depending on a specific case situation – the compliance of P-LCA might rise to the level of that of MFA and Hybrid LCA. For EIO-LCA the same criteria were found to be effected positively by the case studies as on the micro level. The result in the data criteria would not change the overall result here either, though, as compliance in these criteria is too low compared with the other methods. For the criterion of methodological completeness, however, the situation presents itself the same as it does for P-LCA, meaning that case specific compliance of all methods might reach the same level. On the other hand the compliance of EIO-LCA for a broad applicability was disputed by the findings of the case studies. No overall conclusion can therefore be drawn as to the method best suitable on the macro level. Case specific requirements and circumstances but also future development need to be considered in order to select a method for a specific application, a selection, which can be aided by the evaluation of criteria of this thesis.

However, it can be concluded that P-LCA is best suited for micro level application and not suited worse than the other considered methods to macro level applications and can therefore considered the best choice of method to provide information on the life cycle performance of a product system in general terms. This does not mean, though, that in specific situations another method is not equally or better suited. Such specific situations were often the focus of previous studies comparing the strengths and limitations of the considered methods; see for example [SCHEPELMANN ET AL. 2008] and [MINX ET AL. 2007]. The present study can therefore be seen as an evaluation of broad suitability of the life cycle methods providing transparent quantified information on these methods to which evaluations based on case specific conditions may be added. The combination of these two approaches at evaluating the suitability of life cycle methods should be part of further research, especially on the macro level where the general approach taken in this study does not provide unambiguous results. Furthermore additional case studies could enhance the conclusions drawn here. Hybrid LCA was excluded from the case studies as it is methodologically not yet described sufficiently and practical usability is therefore limited. However, future development might change the situation, making case studies on Hybrid LCA more meaningful.

In addition to the assessment of the life cycle methods, the development of a transparent evaluation scheme using a quantitative scoring system was a sub-goal of the study in itself as such a scheme did not exist prior to the study. The hence developed evaluation scheme proved suitable for the evaluation and comparison of the life cycle methods as it provided insight on many different aspects of the potential application of the methods and the theoretical finding gained from it could be confirmed by the conducted case studies. The scheme was applied to the selected life cycle methods only in the course of this thesis but can be used further to evaluate additional methods.

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# Annex 1: Complete results of the theoretical evaluation

**Table 45: Detailed quantitative results of the theoretical evaluation for all sub-criteria on micro and macro level**

| Criteria | Sub-criteria | P-LCA | | EIO-LCA | | MFA | | Hybrid | |
|---|---|---|---|---|---|---|---|---|---|
| | | micro | macro | micro | macro | micro | macro | micro | macro |
| Method documentation | Availability of guidelines or code of conduct | 2 | 2 | 0 | 2 | 0 | 2 | 1 | 1 |
| | Detailed expert documentation | 2 | 1 | 1 | 2 | 1 | 2 | 0 | 0 |
| | Availability of standardisation for method | 2 | 1 | 1 | 1 | 0 | 0 | 1 | 1 |
| Applicability | Broad range of goods and services | 2 | 2 | 1 | 1 | 1 | 1 | 2 | 2 |
| | Broad range of tasks | 2 | 1 | 1 | 2 | 1 | 1 | 2 | 2 |
| Stakeholder acceptance | Inclusion of stakeholders | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | Method application by industry | 2 | 1 | 0 | 0 | 0 | 1 | 0 | 0 |
| | Method application by policy makers | 2 | 2 | 0 | 2 | 0 | 2 | 0 | 0 |
| Objectivity | Reproducibility | 1 | 1 | 2 | 2 | 1 | 1 | 0 | 0 |
| | Influence of assumptions | 1 | 1 | 0 | 1 | 2 | 2 | 1 | 1 |
| Scientific soundness | Validation/Verification checks | 2 | 1 | 1 | 1 | 2 | 2 | 1 | 1 |
| | Plausibility of results | 2 | 1 | 0 | 1 | 1 | 2 | 2 | 2 |
| Methodological completeness | Defined for system boundary | 1 | 0 | 0 | 2 | 0 | 2 | 1 | 2 |
| | Defined for multifunctional situations | 2 | 1 | 1 | 1 | 2 | 2 | 2 | 1 |

| Criteria | Sub-criteria | P-LCA | | EIO-LCA | | MFA | | Hybrid | |
|---|---|---|---|---|---|---|---|---|---|
| | | micro | macro | micro | macro | micro | macro | micro | macro |
| | Suitable for comprehensive environmental assessment | 2 | 2 | 1 | 1 | 0 | 0 | 1 | 1 |
| | Enables analysis of whole life cycle | 2 | 2 | 1 | 1 | 2 | 2 | 2 | 2 |
| Data quality | Data characteristics | 2 | 1 | 0 | 1 | 2 | 2 | 2 | 2 |
| | Independent review | 2 | 2 | 2 | 2 | 0 | 2 | 2 | 2 |
| | Data representativeness | 2 | 1 | 1 | 2 | 2 | 2 | 2 | 2 |
| | Data documentation | 1 | 2 | 1 | 1 | 2 | 2 | 1 | 2 |
| Availability of software tools | Number of available tools | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 |
| | Variation in licence models | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 |
| Communicability of methods | Clarity of method | 1 | 1 | 1 | 2 | 2 | 2 | 0 | 0 |
| | Comprehensible calculation and transparency | 2 | 1 | 1 | 2 | 1 | 2 | 0 | 0 |
| | Established communication | 2 | 2 | 0 | 0 | 0 | 2 | 0 | 0 |
| Data availability and accessibility | Data coverage of the whole life cycle | 2 | 2 | 1 | 1 | 2 | 2 | 2 | 2 |
| | Availability of inventory data for different regions | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 |
| | Availability of inventory data for all relevant impact categories | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 |
| | Publicly accessible inventory databases at affordable cost | 0 | 2 | 0 | 2 | 0 | 2 | 0 | 2 |

## Annex 2: Overview of impact assessment results of the case studies

**Table 46: Impact assessment results of Copper sheet in the EU-15 and the Aluminium composite material**

| Category | Unit | Copper Sheet | | Aluminium composite | | |
|---|---|---|---|---|---|---|
| | | P-LCA | EIO-LCA | P-LCA | | EIO-LCA |
| | | | | Production & Use | Life Cycle | |
| Abiotic Depletion | kg antimony eq. | 190 | 130 | 0,282 | 0,086 | 0,070 |
| Global Warming | kg CO2 eq. | 973 | 51300 | 47,272 | 15,170 | 28,300 |
| Ozone Layer Depletion | kg CFC-11 eq. | 0 | 1 | 0,000 | 0,000 | 0,001 |
| Human Toxicity | kg 1,4-dichlorobenzene eq. | 38 | 39100 | 28,278 | 3,435 | 11,600 |
| Freshwater Aquatic Ecotoxicity | kg 1,4-dichlorobenzene eq. | 1 | 6020 | 0,464 | 0,236 | 3,680 |
| Marine Aquatic Ecotoxicity | kg 1,4-dichlorobenzene eq. | 189500 | 79500000 | 87011 | 11158 | 32800 |
| Terrestrial Ecotoxicity | kg 1,4-dichlorobenzene eq. | 1 | 5540 | 0,123 | 0,019 | 0,368 |
| Photochemical Oxidation | kg ethylene eq. | 1 | 870 | 0,034 | 0,021 | 0,741 |
| Acidification | kg SO2 eq. | 4 | 386 | 0,193 | 0,053 | 0,151 |
| Eutrophication | kg PO4--- eq. | 50 | 31 | 0,010 | 0,003 | 0,012 |

**Table 47: Impact assessment results of the production of PE-HD and PE-LD in Europe**

| Category | Unit | PE-HD | | | PE-LD | | |
|---|---|---|---|---|---|---|---|
| | | P-LCA | EIO-LCA | | P-LCA | EIO-LCA | |
| | | | High price | Low price | | High price | Low price |
| Abiotic Depletion | kg antimony eq. | 0,040 | 0,011 | 0,008 | 0,031 | 0,012 | 0,008 |
| Global Warming | kg CO2 eq. | 1,89 | 4,33 | 3,29 | 2,06 | 4,69 | 3,32 |
| Ozone Layer Depletion | kg CFC-11 eq. | | 0,0003 | 0,0002 | | 0,0003 | 0,0002 |
| Human Toxicity | kg 1,4-dichlorobenzene eq. | 0,854 | 1,350 | 1,020 | 0,032 | 1,460 | 1,040 |
| Freshwater Aquatic Ecotoxicity | kg 1,4-dichlorobenzene eq. | 0,167 | 0,928 | 0,704 | 0,001 | 1,010 | 0,711 |
| Marine Aquatic Ecotoxicity | kg 1,4-dichlorobenzene eq. | 74 | 2490 | 1890 | 106 | 2690 | 1910 |
| Terrestrial Ecotoxicity | kg 1,4-dichlorobenzene eq. | 0,0001 | 0,0529 | 0,0401 | 0,0001 | 0,0573 | 0,0406 |
| Photochemical Oxidation | kg ethylene eq. | 0,012 | 0,145 | 0,110 | 0,013 | 0,158 | 0,111 |
| Acidification | kg SO2 eq. | 0,006 | 0,014 | 0,010 | 0,008 | 0,015 | 0,011 |
| Eutrophication | kg PO4--- eq. | 0,0004 | 0,0012 | 0,0009 | 0,0005 | 0,0013 | 0,0009 |

**Table 48: Impact assessment results of the production of HIPS and PA 6.6 in Europe**

| Category | Unit | HIPS | | | PA 6.6 | | |
|---|---|---|---|---|---|---|---|
| | | P-LCA | EIO-LCA | | P-LCA | EIO-LCA | |
| | | | High price | Low price | | High price | Low price |
| Abiotic Depletion | kg antimony eq. | 0,037 | 0,015 | 0,010 | 0,055 | 0,030 | 0,027 |
| Global Warming | kg CO2 eq. | 3,40 | 5,78 | 3,97 | 7,89 | 11,90 | 10,70 |
| Ozone Layer Depletion | kg CFC-11 eq. | | 0,0004 | 0,0002 | | 0,0007 | 0,0007 |
| Human Toxicity | kg 1,4-dichlorobenzene eq. | 0,194 | 1,800 | 1,240 | 0,145 | 3,710 | 3,320 |
| Freshwater Aquatic Ecotoxicity | kg 1,4-dichlorobenzene eq. | 0,012 | 1,240 | 0,851 | 0,050 | 2,550 | 2,280 |
| Marine Aquatic Ecotoxicity | kg 1,4-dichlorobenzene eq. | 112 | 3310 | 2280 | 408 | 6840 | 6110 |
| Terrestrial Ecotoxicity | kg 1,4-dichlorobenzene eq. | 0,0070 | 0,0706 | 0,0485 | 0,0043 | 0,1460 | 0,1300 |
| Photochemical Oxidation | kg ethylene eq. | 0,010 | 0,194 | 0,133 | 0,002 | 0,400 | 0,357 |
| Acidification | kg SO2 eq. | 0,012 | 0,018 | 0,013 | 0,029 | 0,038 | 0,034 |
| Eutrophication | kg PO4--- eq. | 0,0008 | 0,0016 | 0,0011 | 0,0084 | 0,0034 | 0,0030 |