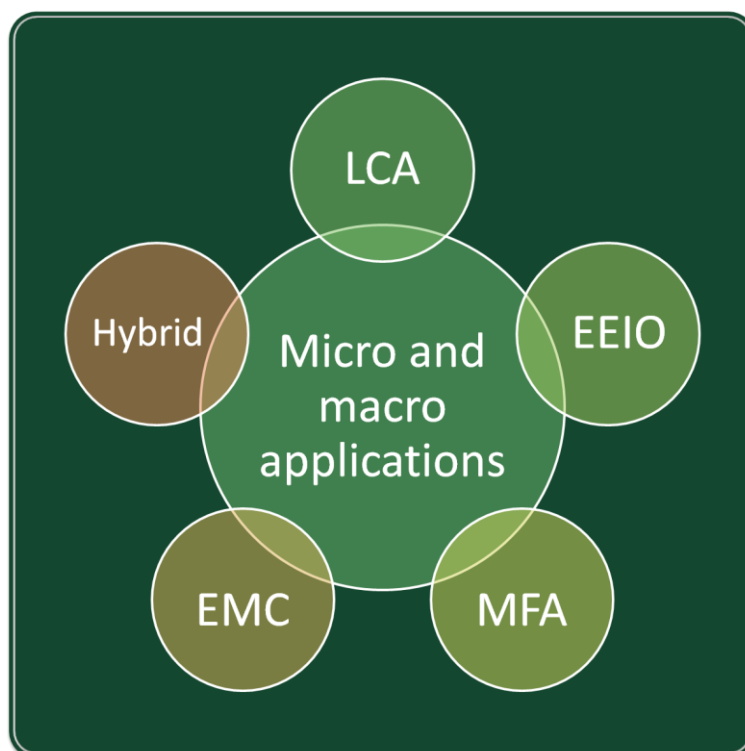# JRC Scientific and Technical Reports

Evaluation of environmental life cycle approaches for policy and decision making support in micro and macro level applications

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Evaluation of environmental life cycle approaches for policy and decision making support in micro and macro level applications

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Executive Summary

Background

The European Commission (EC) has strengthened environmental and sustainability oriented policies and strategies by introducing Life Cycle Thinking. Amongst others, this is a key consideration in the Integrated Product Policy Communication, the two Thematic Strategies on the Sustainable Use of Natural Resources and on the Prevention and Recycling of Waste, as well as in the Sustainable Consumption and Production (SCP)/Sustainable Industry Policy (SIP) Action Plan.

Reliable and scientifically robust life cycle methods are required to support the implementation, monitoring and assessment needs of these strategies and associated policies.

Project goal and scope

This project analyses ***different life-cycle methods*** and provides an evaluation of their current ***suitability for assessing environmental impacts in micro level and macro level situations***.

The micro perspective is typically connected to decision making related to specific products or product groups. This is applicable both in the business and policy domains. 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. It may similarly want to communicate the environmental performance of a product.

The macro perspective, on the other hand, is linked to policy questions involving e.g. a nation or a broader region like the EU-27 or an entire business sector. For instance, the monitoring of decoupling between economic growth and overall environmental impact of the EU-27 consumption system, as addressed in the thematic strategy on resources, is an important case where a life cycle approach is required. Similarly, life cycle methods can provide beneficial insights in e.g. scenario/impact analysis for policies.

Within this study, the following life cycle methods are considered:

- **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 14040-44.

- **Sector-based Economic 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

- **Material flow analysis (MFA):** assesses material and substance flows across generally national boundaries and between processes

In addition, the following combinations, or hybrids, are considered:

- **Environmentally weighted material consumption (EMC):** combines material flows, as in MFA, with environmental impacts for each material estimated using LCA

- **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.

A detailed description of these methods is provided in chapter 2.

Evaluation scheme

The evaluation here is based on *11 criteria* covering the following issues:

- General criteria: (1) method documentation and transparency, (2) applicability, (3) stakeholder acceptance, (4) objectivity in application, (5) communicability of method

- Methodological criteria: (6) scientific soundness, (7) methodological completeness

- Technical criteria: (8) availability of software tools, (9) suitability for time dependent models

- Data criteria: (10) data availability and accessibility, (11) data quality

For the definition of each criterion and to support a transparent assessment, different sub-criteria were developed. The total number of sub-criteria is 33. Chapter 3 provides a detailed description of the evaluation scheme.

A quantitative scoring system was then applied. Each sub-criterion was allocated a value on a scale from 0 to 4; ranging from "no compliance" of the method to "complete compliance".

The main evaluation is related to the methods suitability in micro and macro scale applications at the present time (chapter 4.1). A further analysis was then made considering a 10-years future scenario (chapter 4.2), based on the likely

developments/improvements of the different methods from ongoing research projects and activities (except for EMC). These projects are expected to improve the scores of a few of the sub-criteria of the scheme in this time frame.

It should be noted that not all criteria considered in this evaluation are of equal importance. To take this into account in a structured, transparent manner, an additional analysis was conducted in which the criteria were weighted and the scores cross-compared. The results are presented in the annex of this report.

Results – Micro Level

Regarding the *micro level,* process-based LCA is the most developed approach, with complete compliance in many sub-criteria. This result will not likely change significantly over the next 10 years. The method is scientifically sound, well documented, transparent and widely accepted by stakeholders.

The Hybrid LCA method does not play a significant role at this time but has the potential to become more suitable and relevant. It offers the possibility at the micro level to combine some of the advantageous of both process and EIO- LCA. It is also expected that some of the current problems can be improved in relation to documentation, communicability and stakeholder acceptance.

EIO-LCA, on the other hand, is not expected to become significantly more relevant for micro level applications than it is at the moment. This is not surprising, as it is developed with primarily macro-scale data. The method has, however, good performance with regard to reproducibility and documentation criteria. This is equally reflected by the low scores for plausibility and stakeholder acceptance criteria. These shortcomings are not likely to be overcome at this level, even though some improvements are expected with regard to data availability and communicability.

MFA currently has a more diverse situation in relation to the criteria, as well as being somewhat different to the other approaches in terms of application scope at this level. MFA has complete or no compliance with several criteria. Stakeholder acceptance, method documentation and transparency are all low. But it has good compliance in relation to objectivity criteria as well as the availability of software and ease of communication of the results.

EMC is found to be suitable in principle for micro level applications, but it must be again kept in mind that the method was clearly developed with a macro focus and also has a somewhat different application scope as outlined above.

Results – Macro Level

On the *macro level* the approaches generally have a similar performance against the criteria.

On the whole, the methods have different strength and weaknesses, implying that it may be beneficial to use more than one in applications where the methods can be applied interchangeably.

Process LCA has generally a lower overall suitability in comparison to application at the micro level. The documentation and transparency for use at this scale have weak points. System boundaries are less well defined, the application level by industry is lower, and data characteristics are of lower quality. Stakeholder acceptance is still fairly high. Both data quality and scientific soundness have room for improvement in the coming years.

EIO-LCA has a much higher applicability than on the micro level, reflecting again the scope of the underlying data. Improved performance is clear at this scale in the method description, stakeholder acceptance and the communicability of the method, its suitability for time specific modelling, data availability and acceptance by stakeholders.

For Hybrid LCA, the applicability is as high as on the micro level and the good results for the data criteria are more pronounced. Otherwise the results are similar on both application levels due to combination of P-LCA and EIO-LCA.

MFA improves greatly against the criteria for use at the macro scale. In contrast to the micro level, MFA has a much better results for documentation and transparency. The results for stakeholder acceptance and data availability increase significantly.

EMC achieves the best result of all five evaluated methods for methodological completeness on the macro level. EMC has as well higher results on the macro level, though for different reasons but again reflecting the scope of the approach. The improvement is not caused by a few specific criteria but due to an overall improvement.

Taking into account the next 10 years, a similarly comparable situation is still predicted across the methods. All methods are expected to improve some of their weak points, with the greatest improvement potential within 10 years revealed for Hybrid LCA.

Concluding remarks

Some of the methods analysed are interchangeable, while others are complementary. This will depend on the situation in which they are applied and their scope.

Where methods are not interchangeable, based on their scope and the scope of the application being addressed, the most appropriate method will still need to be used – irrespective of the current/future limitations.

In general, P-LCA, EIO-LCA, and Hybrid-LCA will be interchangeable in many applications, while MFA and EMC will usually have a different scope.

For assessing specific products or product groups, micro applications, generally P-LCA or Hybrid-LCA will be the most applicable methods depending on the scope of the application. For macro applications, use of all interchangeable methods is recommended due to existing limitations and pending further detailed, independent insights on the methodological strengths/weaknesses.

Acknowledgments

Peer review

1   Introduction

Policy background:

In June 2001, the European Council in Göteborg adopted the Sustainable Development Strategy, renewed in June 2006 for the enlarged EU. One of its core objectives is to decouple environmental degradation and resource consumption from economic and social development. However, the measurement of decoupling remains one of the most important and, yet, challenging issues for the European Union's services, member states, regions and cities that are committed to improve the quality of life and the state of the environment. To help address this challenge a new approach – Life Cycle Thinking (LCT) – is being integrated into EU strategies, becoming now an important element of European environmental policy.

In June 2003, the European Commission adopted the Integrated Product Policy Communication, to improve the environmental performance of products throughout their life cycles, i.e. from raw material extraction, through processing and production, to use (or service delivery), re-use, recovery, end of life treatment, and disposal of remaining waste ("cradle-to-grave" approach).

In December 2005, the Thematic Strategy on the Sustainable Use of Natural Resources (TS Resources) further emphasised the important role of LCT in EU policy making, focusing on decoupling economic growth from impacts on the environment in a life cycle perspective.

At the same time the related Thematic Strategy on the Prevention and Recycling of Waste was adopted, including a number of provisions that seek to integrate life cycle thinking into waste policy and to link EU waste policy more directly to the objective of reducing the negative impacts on the environment related to the use of resources, the production and consumption of products, and the management of waste.

Specific policies that are founded on the principles of Life Cycle Thinking are e.g. the Energy-using-Products Directive 2005/32/EC and the Eco-label Regulation No. 1980/2000. In 2008, the new Sustainable Consumption and Production (SCP) Action Plan further strengthened the role of LCT and the coordination among these policies in order to improve the overall environmental performance of products throughout their life-cycle, to boost the demand for better products and production technologies and to help consumers in making informed choices.

Micro and macro applications:

Depending on the level of policy/decision-making and the type of information needed there is a wide range of existing life-cycle based information which are used for these policies. Such information generally refers to a micro level (single

product/process/technology/site) or to a macro level perspective (National/EU policy making).

The broad range of needs may have an influence on which methodologies and underlying data are most suitable to provide the required life-cycle based information. It is possible that some specific methods are more suitable for micro-level analysis, others for macro policy support, while in other situations method integration in the form of a hybrid approach could be the best solution. Equally, in some cases, methods can provide complementary insights.

This study therefore evaluates five life cycle based methods. The evaluation here encompasses two scopes: a product and process perspective on the micro level and a monitoring or analysis perspective on the macro level. In addition, the long-term potential of each method is evaluated (see chapter 4.2). For this the estimated situation 10 years from now is considered.

The micro perspective is typically connected to decision making related to specific products or product groups. This is applicable both in the business and policy domains. 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. Equally, it may want to communicate the environmental performance of its products.

The International Reference Life Cycle Data System (ILCD) Handbook defines micro-level decision support as: "Life cycle based decision support on micro-level, i.e. typically for questions related to specific products. "Micro-level decisions" are assumed to have limited and no structural consequences outside the decision-context, i.e. they are supposed not to change available production capacity. "[1]

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 business 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 on resources, is an important case where a life cycle approach is required. Similarly, life cycle methods can provide beneficial insights in e.g. scenario/impact analysis for policies.

The ILCD Handbook defines macro-level decision support as: "Life cycle based decision support at a strategic level (e.g. raw materials strategies, technology scenarios, policy options). "Meso/macro-level decisions" are assumed to have structural consequences outside the decision-context, i.e. they are supposed to change available production capacity."[1]

A list of examples of uses for which the obtained life cycle information can be applied is given in Table 1.

Table 1: Examples of uses of the life cycle based information classified according to whether they focus on the micro or the macro level, as defined for the purposes of this study [1]

Level of perspective	Possible applications of the life cycle information
Micro	Identification of Key Environmental Performance Indicators (KEPI) of a product group for Ecodesign / simplified LCA
Micro	Weak point analysis of a specific product
Micro	Detailed Ecodesign / Design-for-recycling
Micro	Comparison of specific goods or services
Micro	Benchmarking of specific products against the product group's average
Micro	Development of life cycle based Type I Ecolabel criteria
Macro	Forecasting & analysis of the environmental impact of pervasive technologies, raw material strategies, etc. and related policy development
Macro	Basket-of-products (or -product groups)type of studies
Macro	Identifying product groups with the largest environmental impact
Macro	Identifying product groups with the largest environmental improvement potential
Macro	Monitoring environmental impacts of a nation, industry sector, product group, or product

Methods considered:

For this evaluation, the following life cycle methods are widely used and were therefore selected to be studied in further detail:

- **process-based LCA**, according to ISO 14040-44 (P-LCA);

- sector-based Economic **Input-Output LCA** (EIO-LCA);

- **Material Flow Analysis** (MFA);

Combinations of these are also considered and some examples were equally analysed:

- **Hybrid Approach** between P-LCA and EIO-LCA (Hybrid LCA)

- **Environmentally weighted Material Consumption** (EMC)

The inclusion of MFA is based on the fact that even though it does not include an environmental impact assessment is able to provide valuable information on the basic physical flow data, to which impact factors can be linked.

The methods can be used interchangeably in some applications, or in a complementary manner in others. This issue was not investigated in this study,

although this is somewhat self-evident from their scope and use in current practice. However the study does highlight if the methods are interchangeable then what are the relative strengths and weaknesses, as well as if there is a clear preference or more than one should be used in parallel.

Steps of the analysis:

As a first step, a basis for the evaluation is provided by analysing and characterising the considered methods (see chapter 2). A transparent and comprehensive evaluation scheme is then developed, which ensures balanced and reliable conclusions in the subsequent evaluation (see chapter 3). Present situation and future potentials are then evaluated separately (see chapter 4) and each method discussed individually (see chapter 5). This allows for a final comparison of the methods from the perspective of the micro and macro level applications (see chapter 6). Further comparison for more specific applications is not presented.

It shall be noted that this study does not aim to identify the best method for every possible situation or application, as there is not one method that fits all needs. Neither does this study assume that the evaluated methods are interchangeable in every decision making situation, nor that only one should be used where they are interchangeable. Rather the study aims to evaluate the strengths and weaknesses of each of the methods.

Furthermore, a high score in the quantitative evaluation should not be read as perfection, but rather compliance with the aspects taken into account as stated in chapter 3 and Annex 1.

2 Characterisation of the Life Cycle Methods

In this chapter the considered life cycle methods are analysed and characterised as a basis of the evaluation of the suitability of the methods to the different scope situations. However, this does not constitute a comprehensive description of the selected life cycle methods, but rather an introduction. Additional information may be taken into account for the evaluation, as stated in the respective sections. For more detailed information on the methods, see the various references given.

It should be noted that e.g. the calculation of impact indicators in all methods (except MFA, where this is irrelevant) can be based on the same framework, approaches, and data. Distinctions across methods are therefore more in terms of the inventory estimates (emissions/resource consumption). Strengths and weaknesses of how impact indicators are then calculated from emission/resource consumption data will be essentially the same for all methods. However, the number of impact categories (climate change, acidification, toxicity effects, etc) that can be addressed will differ depending on what inventory data are available in a sufficiently robust manner. The strengths/weaknesses of the impact assessment calculations are therefore not taken into account in this project, beyond consideration of the extent to which the inventory/resource consumption data support this.

2.1 Characterisation of P-LCA

2.1.1 Methodological description

Process-based Life cycle assessment (P-LCA) is defined in general terms in the international standards ISO 14040 and 14044, while noting that not all studies are conducted in compliance with these standards.

Essentially a process LCA consists of combining data for emissions and resources for different processes that are associated with the supply chain, use, and end-of-life phases of a specific product (goods or services). This provides an inventory. From this inventory, using impact assessment methodologies, indicators are calculated of associated impacts in terms of the environment, human health, and resource consumption. The same methodologies are used for this impact assessment as can be applied in other life cycle related approaches.

The underlying principles of P-LCA include:

- Consideration of the entire life cycle of a product (supply chain, use, and end-of-life)

- Use of an iterative approach

- Functional unit to facilitate comparison across different products

- Reliance primarily on natural science

The basic stages of a P-LCA are the 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.

There is no definite set of impact categories which have to be considered in P-LCA. The selection of the categories should take into account, and be consistent with, the goal and scope of the study; precisely the impact categories should be environmentally relevant and scientifically sound for the product being assessed [2].
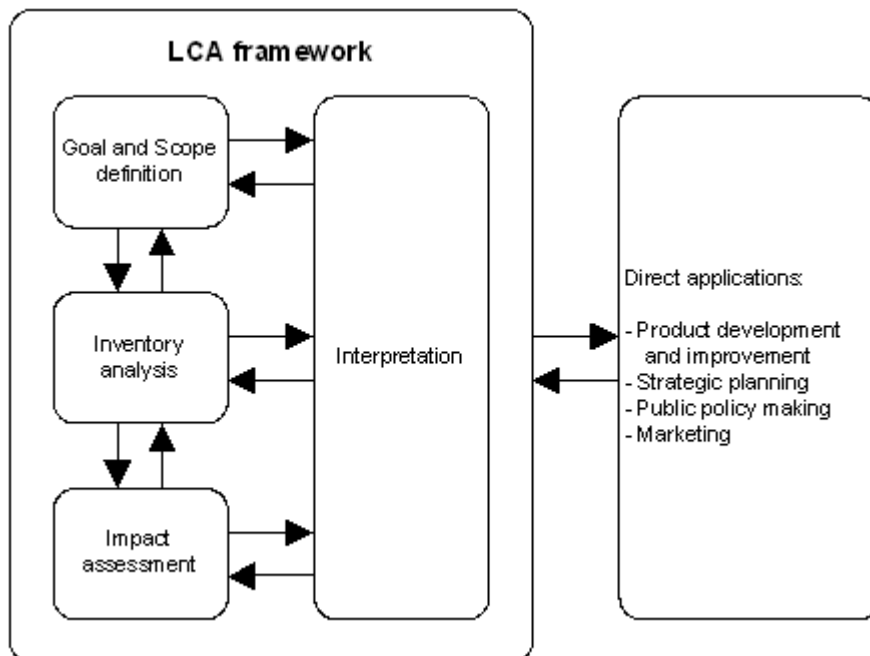
Figure 1:   **Stages of a P-LCA [2]**

2.1.2   Development of P-LCA

2.1.2.1   History

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 laid in energy. Therefore discussions about the assignment of different environmental impacts were of no importance [3].

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 [4].

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 [5].

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 [6].

2.1.2.2   Recent developments

Interest on LCA on the political level is reflected in different policies such as the European Integrated Product Policy (IPP) and the Sustainable Consumption and Production (SCP) Action Plan as well as projects like the European Platform on LCA, led by the European Commission. Furthermore there is now a wide range of initiatives and societies dealing with the subject of LCA. This includes the UNEP-SETAC Life Cycle Initiative, which is promoting interactions at a global scale and complementing many national/regional activities. On a national level there are, e.g., the Brazilian LCA Network, the Japanese AIST - Research Center for Life Cycle Assessment, the Nordic Life Cycle Association or German Network Life Cycle Data.

The standardisation for P-LCA has been revised and the current versions of ISO 14040 and 14044 were published in 2006. The revision aimed at enhancing the readability and correcting mistakes as well as inconsistencies [2], [7], [8].

To facilitate Life Cycle Thinking in support to the policy areas mentioned in the introduction to this report, the European Commission initiated the project "European Platform on Life Cycle Assessment. This Platform has the objective to promote LCA in business and in public administrations within the European Union, by providing technical guidance and expertise. This includes the recent launch of the International Reference Life Cycle Data System (ILCD) Handbook, which provides the basis for coherence and quality assurance in LCA data and applications.

2.1.3   Major applications of P-LCA

P-LCA has been applied in many different decision making situations. On the one hand its uses include strategic statements on a political or scientific level regarding the environmental performance of products or 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 [9]. 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   Identified gaps in the method

2.1.4.1   Methodological gaps

Methodologically the P-LCA intends to consider the entire life-cycle of the investigated goods/services, which is not possible in a perfect sense in the majority of cases. The system modelled needs to be "cut-off" at some point in order to manage its complexity (i.e. not to consider the supplier of the supplier of the supplier). Since there is no clear specification in wide use at this time on the cut-off criteria, the results may differ widely in some cases. The same applies to other necessary assumptions, such as allocation procedures when there is more than one product from a process and it is necessary to only assess the impacts associated with one. These assumptions are not regulated in detail in wide use, while e.g. the ILCD Handbook is now recently available.

2.1.4.2   Data gaps

Data collection is time and cost consuming, since all processes in a life cycle need to be modelled. Equally, the quality (e.g. concerning age and geographical dependencies) needs to be specified clearly in order to ensure transparent and comparable conclusions. Of course there are a variety of commercial as well as publicly available databases which can be used, as well as some emerging data networks.

The process data used may be proprietary and confidential, which leads to difficulties in both reproducibility and transparency. This is being overcome more recently through e.g. requirements for independent review to support user confidence.

Regional/temporal differences are often not reflected in the data. Since existing data were usually collected for operations in developed countries there can be a lack

of specific data for e.g. developing countries. Clear exceptions include where e.g. industry associations have international operations and collect associated data, or where operations have been modelled related to goods produced primarily in developing countries but consumed in developed ones. The relevance of this issue will therefore be on a case by case basis.

2.1.4.3   Necessary future research

In addition to the research needed for methodological and data gaps, the impact assessment still lacks sound approaches for certain categories such as renewable resources [74].

The applicability of LCA needs to be facilitated, e.g. with regard to the differentiation of the approach for different regions and industries.

A more detailed insight is available in the work conducted within e.g. the CALCAS project where necessary research topics were analyzed in detail [10].

2.1.5   Methodological research

2.1.5.1   Ongoing development work

A lot of research is ongoing in the context of LCA at the national, regional, and global levels.

The European Platform on LCA, as one example, strives to strengthen life cycle thinking in policies as well as in the development of goods and services. In order to achieve these objectives the Platform will enhance the methodological harmonisation of LCA and facilitate access to LCA data. To this purpose, the European Commission's JRC IES is coordinating the development of the International Reference Life Cycle Data System (ILCD), which is composed of a series of guidance handbooks and an open data network. The latter is expected to include datasets from the European Reference Life Cycle Database (ELCD) [11].

For the impact assessment there are still environmental issues not addressed or not adequately addressed by research, e.g. local categories such as noise and odour or the wide subject of land use. Data quality and uncertainty in LCA are problems still not completely solved.   As stated in the introduction, however, many of these issues will be equally applicable to other methods as they rely on the same impact assessment data.

Regarding the gaps in impact assessment the ILCD handbook [12] will contribute as will the UNEP-SETAC Life Cycle Initiative [13]. More details on the topic of ongoing development work can be found in the analysis done within the CALCAS project, see [14]. These include, but are not limited to issues of allocation, the

introduction of time into the modelling and work on impact assessment, e.g. on regionalized assessment.

In addition there is development on the references used for conducting LCA studies: best practice might differ across industries and it might therefore be advisable to consider sector specific approaches.

2.1.5.2   Foreseen development work

Future development work might include development of social indicators and the further development of consequential LCA, especially in regard to guidelines. Consequential LCA takes into account the consequences to the material and energy flows, as caused by changes in the life cycle [15]. In addition the topics mentioned in the previous paragraph will continue to be developed further.

2.1.5.3   Improvement in data basis

It is imperative to expand the existing, commercially and publicly available databases with new, specific processes (not just averaged data for an industry or product or service), new geographical areas (not just averaged data from a few studied processes in a country, but specific studies for specific geographical areas), additional emissions and wastes (e.g., size- and composition-resolved particulate matter emissions). It is equally imperative to improve their quality and coherence. All caretakers of data basis strive to expand and improve their data along these lines, while some of the aforementioned activities contribute to this.

Work on the data basis continues in order to advance a widespread application of LCA. This includes some emerging data networks. So far the data consist mainly of inventory data, but will in some cases also be extended by recommendations concerning the impact assessment, such as the European Platform on LCA is planning.

Standardisation of data format seems also necessary to allow the exchange of data between different data bases, while some national and regional recommendations are now available.

2.1.5.4   New application fields

It can be foreseen that in the future LCA will be part of a Life Cycle Sustainability Assessment. Aside from that its role in eco-efficiency applications may increase. More detailed inside into possible new applications and integration with other methods can be found in the analyses of the CALCAS project on options for deepening and broadening LCA, see [16] for more detail.

2.2　Characterisation of EIO-LCA

Economic Input-Output-LCA (EIO-LCA) represents an economy-wide assessment. This includes direct and indirect environmental effects, i.e. effects caused by the business 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 [17].

As the terminology with regard to the LCA approach based on input-output tables is not fixed it should be noted that the term EIO-LCA used here is also commonly referred to as Environmentally-Extended Input Output Analysis (EE-IOA).

2.2.1　Methodological description

EIO-LCA uses economic input-output analysis to map general interdependencies between sectors in the economy of a given region and quantify those relationships (in monetary terms), and then assign environmental factors to the sectors as defined by the I-O tables [17].

The method requires national economic input-output tables. Within the European Union, input-output tables are produced every five years and supply and use tables (SUT) every year by the ESA-95 regulation [18]. Supply and use tables can be used as the basis for IO tables under certain assumptions [19]. These tables are standardized and give data on 60 sectors and product groups with a required maximum lag of three years.

The voluntary National Accounting Matrix including Environmental Accounts (NAMEAs) use the same sector differentiation to provide data for several emissions to air [19]. According to Tukker et al. (2009) the resolution in these 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 [19].

The U.S. I-O table, for example, is published every 5 years. The latest year available is 2002. The U.S. I-O table typically has about 490 sectors, which may be defined relatively narrow (e.g. ready-mixed concrete) or broad (e.g. plastics). Other countries, stated by OECD to have provided I-O tables, are not included in the list, since some of these tables may not be easily obtained for a private person, and most of them have too few sectors to be useful for environmental assessment.

The total economic effect generates environmental emissions across the economy. The I-O table is linked with emission factors to calculate the total emissions associated with an economic demand (e.g., USD 1 demand for electricity). The emission factors are calculated by dividing the total annual emissions from each sector in I-O table (available from publicly accessible databases such as those from

U.S. Environmental Protection Agency) by the total annual output of this sector. The resulting emission factor (in units of emissions/USD) is then multiplied by the output from the sector.

Table 2 shows an extract from the "Leontief Inverse Matrix" corresponding to the 1997 U.S. I-O table for the electric power sector (called "Power generation and supply") [20]. One U.S. dollar of demand for electricity results in a total economic activity of USD 1.73 in the entire U.S. economy, i.e. the total economic effect of a final demand. As a result of one dollar of demand, the electricity sector actually produces USD 1.007 worth of electricity, or 0.7 cents more, because all the other industries in the electricity sector's supply chain also have demand for electricity, worth USD 0.007.

Table 2: **The economic effect of the demand of electricity worth USD 1 in the U.S. economy, based on the 1997 input-output table [20].**

Total for all sectors	1.73 USD
Power generation and supply	1.007
Oil and gas extraction	0.098
Coal mining	0.078
Pipeline transportation	0.034
Rail transportation	0.030
Wholesale trade	0.025
Lessors of nonfinancial intangible assets	0.023
Petroleum refineries	0.022
Legal services	0.020
Real estate	0.019
All other sectors	0.372

Input-Output models do not generally cover the whole life cycle, as information on use and waste management phases is not included[21]. For the use and disposal phase a different data source is therefore needed which means that for these life cycle stages process-based data is often utilized. For example, in an LCA of an automobile, the EIO data would not assess the emissions from driving the vehicle. Process data are needed to add the emissions from the use of the vehicle to the total inventory of vehicle emissions and impacts from all life cycle stages. For approaches covering this limitation see chapter 2.4.

Considered impact categories are not defined for EIO-LCA but various impacts can be included in the calculation depending on what emissions statistics are available for different sectors.

2.2.2   Development of EIO-LCA

2.2.2.1   History

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 [22]. 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. EIO-LCA was developed at Carnegie Mellon University in the mid-1990s.

The EIO-LCA approach has evolved from the necessity to solve practical LCA problems. An early example of the EIO-LCA approach is Joshi's Ph.D. dissertation [23] that documents the need for a combined use of EIO-LCA and process LCA. His journal paper [24] 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 [25] that used process data for the use stage and EIO data for every other stage (but ignored end-of-life treatment), and [26] that extended the automobile inventory analysis to diesel and compressed natural gas.

2.2.2.2   Recent developments

EIO-LCA sector disaggregation (see Chapter 2.4 for description) as part of the hybrid LCA process is a new development.

The issue of the treatment of imported goods, which is stated below, is starting to be addressed by the introduction of multi-region input-output (MRIO) models. Wiedman et. al (2007) e.g. distinguish between linked single-region models and true multi-region models. 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. [27] 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 [28].

2.2.3   Major applications of EIO-LCA

EIO-LCA has been applied to a number of industries including e.g. construction, automobile, energy, transportation, electronics, information technology. A list is found in reference [17]. The level at which these can be assessed is obviously dictated by the level to which the statistical data are available, i.e. generally at the macro scale.

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   Identified gaps in the method

2.2.4.1   Methodological gaps

It is unclear if the boundaries of the life-cycle phases set for process-based LCA (typically for the use and disposal phases) are equally comprehensive for EIO-LCA analysis (typically for assessing manufacturing, excluding the use and end-of-life phase). It is also not clear how imports from other countries should be assessed, as multi-country economic input-output analysis-based LCA models generally do not exist.

The assumption of proportionality of economic flows with environmental effects is also debatable.

EIO-LCA gives average results of an economic sector defined in the I-O tables. From an environmental as well as economic point of view it often simplifies the impacts of imported goods as it treats them the same as domestically made ones, which might lead to over- or underestimations in environmental assessment of imports [19]. For example, production of steel in a country with mostly coal as energy input (e.g., China) would result in higher carbon emissions than in the U.S. where the energy mix includes renewable energy sources with lower carbon emissions. This effect varies with the size and openness of an economy. For example, the U.S. economy is to a large extent self sufficient; with the exception of a few sectors (such as textiles), imports are a small part of the overall demand for products and only small variations in the result are to be expected. In other economies, where imports are more important in the GDP, such as in the smaller economies, this treatment of

imports in the same way as domestic production is a more serious methodological gap. Research concerned with this issue can be found in chapter 2.2.2.2 and 2.2.5.

2.2.4.2   Data gaps

Economic and environmental data are typically not available for specific goods or services, but rather for product groups and service bundles (sometimes referred to as sectors). Data for many environmental categories for sectors are missing and limited in scope to what is collected for sectors for a given economic region. The extent of data availability may differ greatly between the life cycle phases. During an LCA study this turns out to be a problem as the availability, the level of detail and the quality of the data available can vary greatly for different studies:

- emissions data may not be available for all sectors of the economy modelled in the I/O data, including at the same levels of disaggregation. Matching can be an issue.

- emissions/resource use data may not be very comprehensive for many impact categories and may not always cover the main emissions related to a specific sector.

Based on Tukker et al. (2009) current data gaps also concern the availability of a resolution in the IO tables, which allows distinguishing sufficiently between sectors with different impact intensities, linkages between different economies and the availability of corresponding environmental data which mainly covers emissions related to climate change.

2.2.4.3   Necessary future research

Many of the topics raised above, especially with regard to data provision lead to necessary future research. This especially concerns the need to provide IO tables with a higher resolution and corresponding environmental information. It is also necessary to formalize the boundary setting in the methodology, and to work out the treatment of imported, products in the analysis of the final product under study. Data gaps should be addressed, quality should be raised by eliminating uncertainties in collection and interpretation, and representativeness and technological correlation between data and studies should be enhanced. Also, a standardisation of the approach would assist its acceptance and help to improve the range of application.

2.2.5   Methodological research

2.2.5.1   Ongoing development work

Though not related to the EIO-LCA methodology itself, the EXIOPOL project constitutes an example of major current research on input-output based environmental assessment. The EXIOPOL project 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 [19, 29] [30]. The work on MRIO models mentioned in 2.2.2.2 is still ongoing as well.

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, by middle 2012, data for the 27 EU countries and 13 other major countries covering more than 30 industries and at least 60 products.[31]

2.2.5.2   Foreseen development work

It can be anticipated that EIO-LCA-type environmental assessment tools will be developed in the future for countries that currently do not have it. This will require the linking of country-specific I-O tables to environmental data vectors, neither of which may be available now. It can be expected that China will develop an EIO-LCA model for energy and greenhouse gas emissions in the future as they have both I-O as well as energy data. It is also expected an EIO-LCA model for the European Union. The EIPRO study aimed at providing an I-O table for the EU-25 for the level of 2003. However, the resulting table is not entirely comparable to the US or Japanese tables, mainly due to the used data basis and necessary adaptations: data used were based on national tables of the EU-15 of 1990 (accumulating to 72 % of the EU-25 economy in 1990) as provided by the OECD. This data was scaled up to the EU-25 economy of 2003 by applying economic growth. The OECD tables constituted of a 35 x 35 matrix but since a more detailed representation was required the OECD matrix was transformed to fit the dimension of the larger US matrix using a mathematical procedure (assuming that the industry structure is similar in both the US and the EU) [32].

2.2.5.3   Improvement in data basis

National economic I-O tables are required for a more widespread use of the EIO-LCA method, which then need to be linked to environmental data for each of the I-O sectors to create sector-specific emission factors. Existing economic data are by and large fairly robust, though the agencies refreshing sector definitions need to better follow the change in product and service offerings in an economy. Lots of environmental data are missing in most countries of the world, for example, water use data by industries (let alone products) are not available.

2.2.5.4   New application fields

An EIO-LCA methodology that allows the disaggregation of its sectors (see chapter 2.4 for description) has many application possibilities. It would make the

analysis of hundreds of products and services possible and fairly accessible to the public and other users (government, industry, and academia).

The fields of application of the model are expanding in number. For example, service industries have not been much studied thus far. But biotechnologies and nanotechnologies are changing how industries operate and manufacture products as well as how consumers use them; therefore their study is becoming more and more urgent.

2.3   Characterisation of MFA

Material Flow Analysis (MFA) and Substance Flow Analysis (SFA) are used to characterize the flows and stocks within a defined system, which can be focussed on both the micro as well as the macro level. Spatari et al. reviewed the development of framework, definition of MFA/SFA in their paper [33].

MFA frameworks have been defined ([34], [35], [36]) and in some cases also incorporated into government policy frameworks [37, 38]. The main objective of MFA is to establish the flow patterns of materials and elemental substances in specific systems.

In this study we distinguish between SFA on the micro level and Economy-wide MFA (EW-MFA) on the macro level.

2.3.1   Methodological description

The term Substance Flow Analysis (SFA) is used when referring to specific 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. For example, it can identify spatial reservoirs of materials in use which may become scarce in the future. In addition to resource usage, SFA can be used to analyze consumption patterns of specific materials, and the associated energy and environmental impacts that accompany those materials.

Figure 2 shows a diagram of material stock and flow. "In-use stocks" are located at the centre of Fig. 2 and flows of inputs to the stocks and outputs from the stocks are indicated using arrows. Stocks of materials that form part of the in-use products are expressed as in-use stocks. Disused materials generated from in-use stocks are indicated as outputs from in-use stocks (H). Flow (B) shows input into waste management processes, while flow (D) is output that is dissipated into the environment, e.g., materials dissipated during use by wear, corrosion, and erosion, and disused cables remaining underground. Three possible types of "uncollected

materials" resulting from waste management processes are taken into account: materials in landfill, those mixed into other material's cycle, and those exported to other countries, represented as (E), (F), and (G), respectively. In SFA, all these amounts of flows and stocks will be quantified [39].
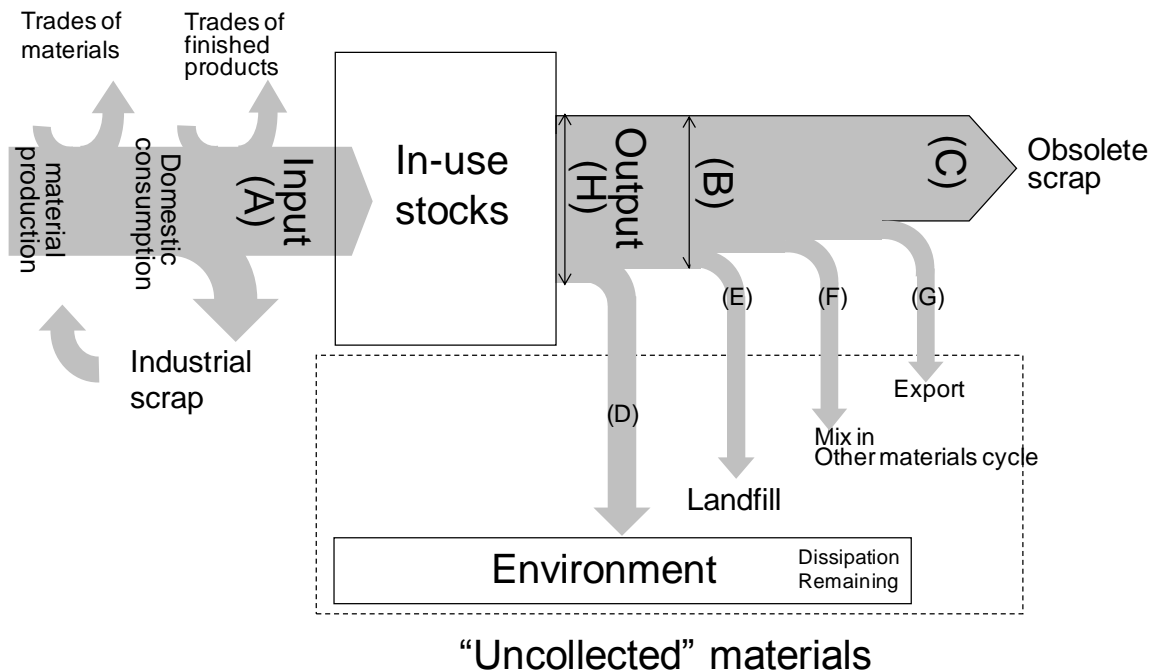
Figure 2: **Schematic diagram of material stock and flow [39]**

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 3. 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. [40] By balancing the physical flows of a country EW-MFA is a satellite account to the System of National Accounts.
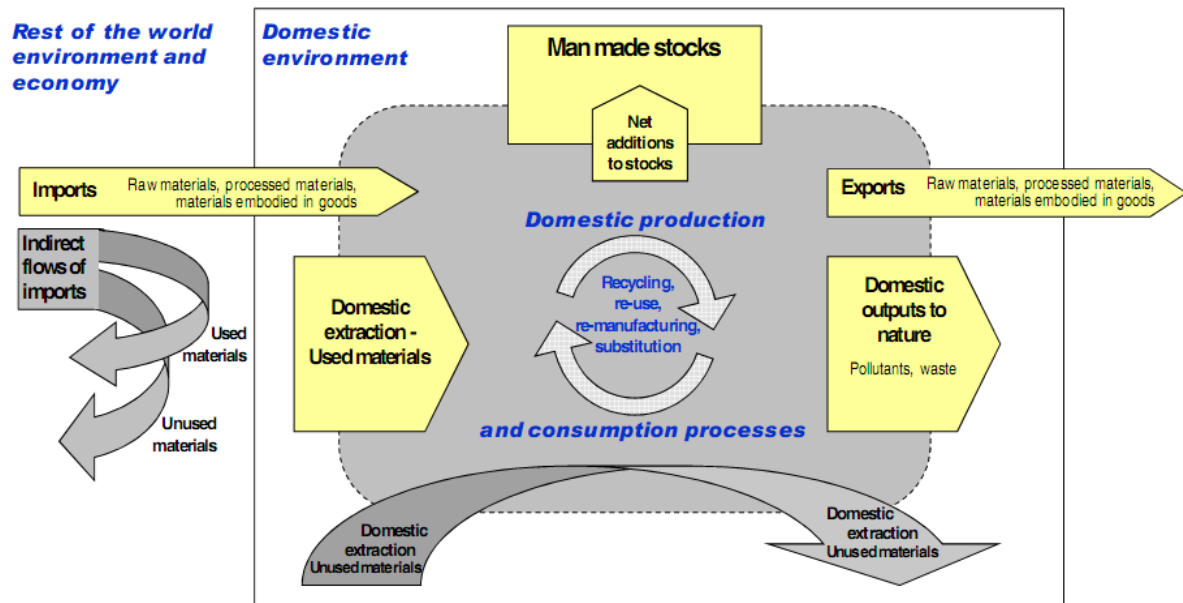
Figure 3: Schematic representation of an economy-wide material balance scheme [41]

2.3.2   Development of MFA

2.3.2.1   History

Spatari et al. reviewed the development of the history of MFA/SFA in their paper [42]: Much SFA work has been carried using steady-state flow models for copper and other metals at national and global scales [42], [43], [44], [45]. In addition, many SFA case studies are published by Conaccount, a research exchange organized by the Wuppertal Institute ([46], [47]). 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 [41, 48].

2.3.2.2   Recent developments

More recently, Zeltner et al. (1999), Binder et al. (2001), Kleijn et al. (2000), and van der Voet et al. (2002) have begun to incorporate dynamic models to examine the flow of goods and substances over extended time intervals [49], [50], [51], [52]. This type of analysis has brought out the potential to investigate stock accumulation in society. Zeltner et al. (1999) and Ayres et al. (2003) have completed dynamic copper flow scenarios for the US and global systems [49], [53]. Zeltner et al. (1999) constructed a dynamic input– output material flux model, which traces the cumulative

life cycle copper flows in the United States between 1900 and 1990 [49]. They use production and consumption data of copper along with select product applications, grouped according to their long and short-term in-use residence times, to show the copper flows into the waste system in 1990, and projections to 2100. Ayres et al. (2003) use time-series production and consumption information and old and new scrap data for copper to estimate existing stocks of copper. They then project future global copper consumption scenarios. [53]

2.3.3   Major applications of MFA

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.[54]

Depending on the focus of the study two basic strategies can be distinguished: dematerialization and detoxification [55]. 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 or also on a global level and it can be applied on e.g. economy sectors or households. [56]

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

2.3.4   Identified gaps in the method

2.3.4.1   Methodological gaps

With regard to this study the missing impact assessment is considered a methodological gap, as is the unclear decision support.

For SFA an inherent methodological gap is the danger of problem shifting as only one substance is regarded.

2.3.4.2   Data gaps

When time series are needed the data availability issues become increasingly difficult. However, data for EW-MFA is available for various – particular developed – countries, though often not exhaustively [57]. For developing countries the availability of data is usually quite limited for MFA/SFA studies.

Another main challenge, especially for dynamic studies, is how to assess the lifetime of the studied product or system. This is one of the most critical parameters related to the urban built environment and often one of the least understood.

2.3.4.3   Necessary future research

Especially, dynamic modelling of MFA/SFA has been conducted since the beginning of this century. That is why further researches are still needed to obtain MFA/SFA case studies to cover the most elements and regions.

2.3.5   Methodological research

2.3.5.1   Ongoing development work

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. Table 3 shows MFA/SFA case studies focusing on EU and individual member states.

2.3.5.2   Foreseen development work

The linkage of each substance flow is one of the most important future tasks in the field of MFA/SFA. Integration of MFA/SFA within LCA is also an important challenge to properly evaluate the environmental impact of materials.

In addition future development is likely to include work on the integration of MFA with economic and social methods or Waste IO.

Table 3:   MFA/SFA case studies focusing on EU and individual member states

Author(s)	Element	Region	Reference
Spatari et al.	Cu	EU	[42]
Graedel et al.	Cu	Germany, EU, World wide	[58]
Gorter J.	Zn	The Netherlands	[43]
Johnson et al.	Ag	France, Germany, EU, World wide	[59]
Johnson et al.	Cr	EU, World wide	[60]
Elshkaki et al.	Pb	EU	[61]
Melo M. T.	Al	Germany	[62]
Kleijn et al.	PVC	Sweden	[51]

2.3.5.3   Improvement in data basis

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. An online portal from the Sustainable Europe Research Institute (SERI) was launched, providing MFA data on a national level [63]. For the US there is a pilot MFA database available, see [64].

There exists no widely applied commercial software specifically designed for conducting MFA/SFS studies. The most common tools used in MFA/SFA studies are still the generic software, like Matlab/Simulink and Excel.

2.3.5.4   New application fields

One of the challenges is to define the applicability of the results of an MFA. The MFA results should be more closely linked to environmental impacts, which would be important in the use as a policy tool.

So far MFA practitioners have not marketed their results appropriately to the relevant stakeholders that can bring about the right changes. Normally a study is carried out and published in a scientific journal, ending with some recommendations of possible applications for policy planners and other stakeholders. To improve the spreading and utilization of results, the scope and application area of the study should be stated clearly from the beginning with an up front analysis on the important stakeholders and the information they are interested in. More attention should also be paid to economic considerations since these are important aspects for the stakeholders. Future development as mentioned above will contribute to new applications as well.

2.4   Characterisation of Hybrid LCA

In practice, many problems that need an LCA analysis require the combined use of the P-LCA and the EIO-LCA models. For example, problems that have many inputs and an extended tree of supply chains, often in multiple countries, call for a 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 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 [65]:

- 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)

- Input-output based hybrid analysis – disaggregates the information given in the input-output tables, and uses process-based data for the use and end-of-life stages

2.4.1 Methodological description

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). Figure 4 shows a schematic of this approach.

Many different variations exist for combining the basic approaches. 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.
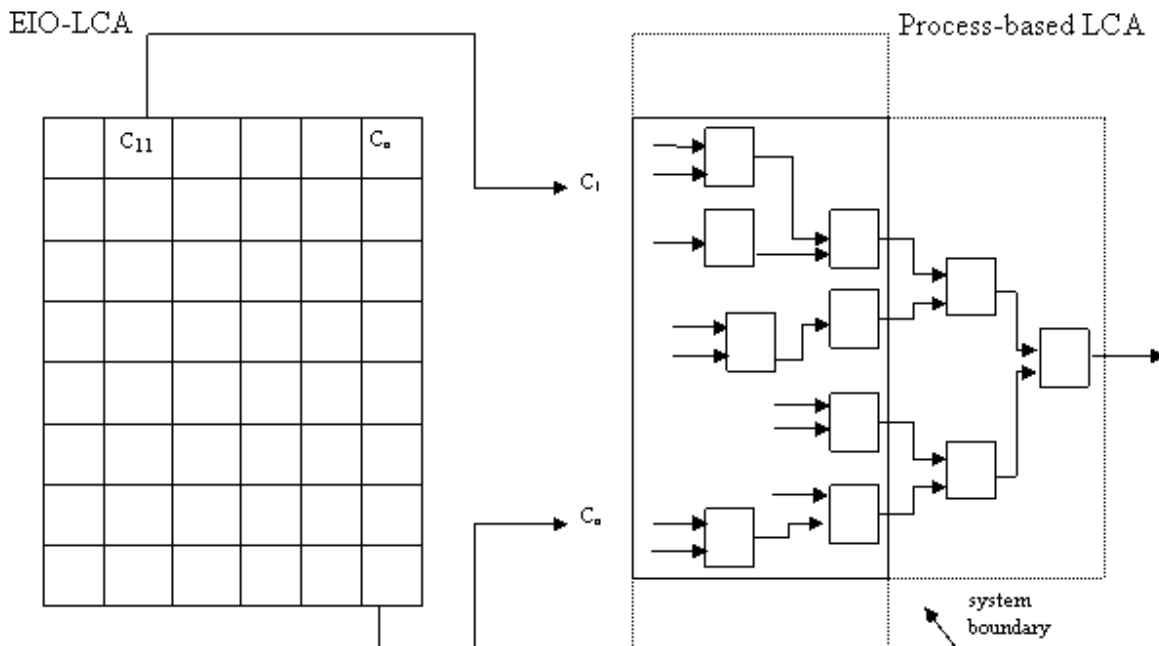
Figure 4: **Use of EIO-LCA Results to Estimate Impacts of a Process [17]**
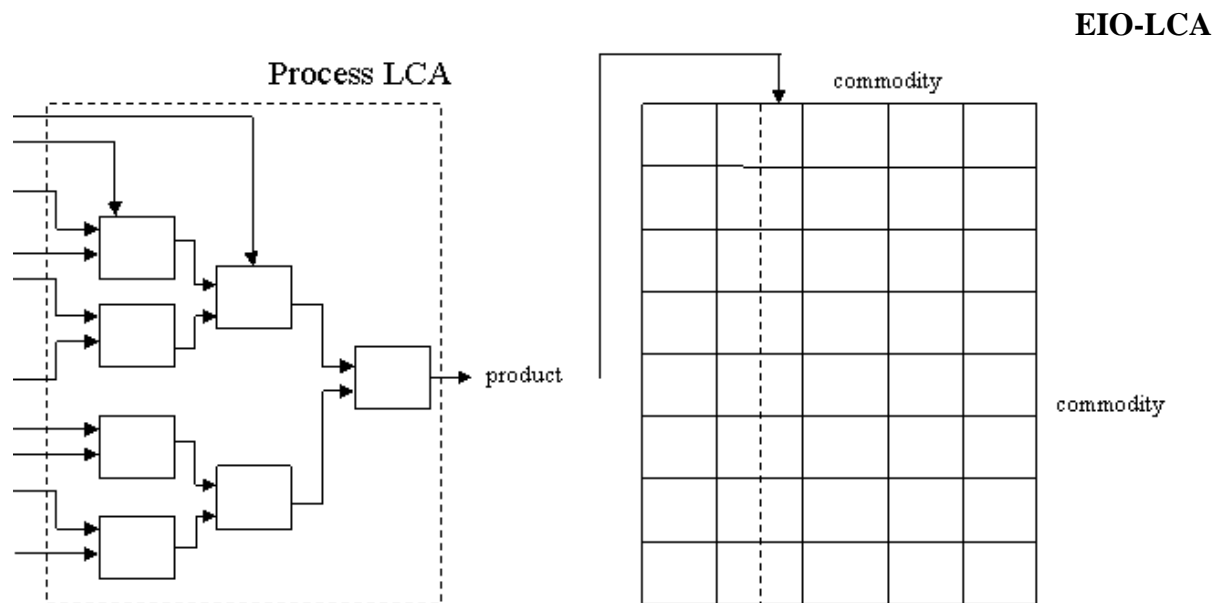
EIO-LCA

Figure 5:   Integration of process model data into EIO-LCA for a hybrid model

Another advanced hybrid LCA approach is the *Integrated hybrid analysis* which disaggregates the information given in the input-output tables, and uses process-based data for a more specific and more useful EIO-LCA analysis. Figure 5 illustrates this concept. For example, the EIO-LCA sector (a column in the EIO-LCA table in Figure 5) „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.

2.4.2   Development of Hybrid LCA

2.4.2.1   History

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 [17].

Pacca and Horvath 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. [66]

2.4.2.2   Recent developments

The popularity of hybrid LCA has grown. Several hybrid LCAs have appeared in print in the last 5 years. For example, in their analysis of coal and natural gas transport versus electricity transmission [67], Bergerson and Lave (2005) estimated the parameters of electric power station processes and then used EIO-LCA for the estimated inputs.

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. [68]

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   Identified gaps in the method

2.4.4.1   Methodological gaps

Since many variations exist for the application of the advanced hybrid analysis, 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 different results. Therefore, it would be important to formalize the methodology to avoid possible problems with incomparable results between studies and lack of guidance as to the boundaries of the analysis. So far it is unclear if the boundaries of the life-cycle phases set for process-based LCA (typically for the use and disposal phases) are equally comprehensive as for EIO-LCA analysis (typically for assessing manufacturing).

In the basic hybrid LCA approach, it is also not clear how imports from other countries should be assessed as multi-country economic input-output analysis-based LCA models do not exist.

The use of the second hybrid LCA approach, which is based on the input-output analysis, is more complicated as the process-based hybrid approach. First, the input-output table used in EIO-LCA (called the total requirements table in input-output analysis), specifically a column and a row corresponding to a product or service in order to be further analyzed, would need to be disaggregated. The disaggregation may be done to provide more specific definitions of products in a sector of the I-O tables. For example, plastics are represented by only one sector in a typical input-

output table while in fact there are many different types of plastics (e.g., polyethylene, polypropylene), so the plastics sector would be a candidate for disaggregation. After the disaggregation is done mathematically, the column in the I-O table (which represents a product or service) would need to be filled with data (in rows) that previously did not exist in the table, i.e., with process-based LCA data on the inputs. For example, for polypropylene all the manufacturing and supply chain impact data would need to be entered from a process data base. The complicated nature of disaggregation has most likely kept the developers of this approach from widespread use of this method.

2.4.4.2   Data gaps

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.

Data restrictions are added due to the data restrictions of the two basic approaches, EIO-LCA and P-LCA.

The most significant data problem in the input-output analysis-based hybrid analysis is the required data intensity. Once a sector in the I-O table (a column) is disaggregated into sub-products, many inputs are needed (in the rows) to make the new column consistent with the rest of the table. In the case of the U.S. EIO-LCA, the number of inputs in the rows can reach more than 400. Very rarely process data are available for many inputs.

2.4.4.3   Necessary future research

It is necessary to formalize the boundary setting in the advanced hybrid LCA methodology, and to work out the treatment of foreign-sourced, or imported, products in the analysis of the final product under study. The input-output analysis-based hybrid approach needs to be made practical (e.g., through a web-based tool) to abridge the difficulty in disaggregating and manipulating input-output tables.

Data gaps should be addressed, quality should be raised by eliminating uncertainty in collection and interpretation, and the representativeness and technological correlation between data and studies should be enhanced. The more process data are available, the better the input-output analysis-based hybrid approach can become.

More practical experience with the hybrid approaches is also needed as so far there have only been a few case studies with demonstration character.

2.4.5 Methodological research

2.4.5.1 Ongoing development work

The EXIOPOL project, as listed in 2.2.5.1 constitutes important ongoing development regarding the hybrid approaches as well [30].

2.4.5.2 Foreseen development work

The advanced as well as the input-output analysis-based hybrid LCA models will only become better and thus more credible if the methodological and data gaps (as identified above) are addressed adequately. Due to a lack of information as to who is developing it, the direction of further progress of the hybrid LCA approaches is not foreseeable.

2.4.5.3 Improvement in data bases

Constant and continuous improvements of the LCA data bases are important.

For improvements regarding the process analysis-based LCA, see 2.1.5.3.

Input-output analysis-based data bases also need to be periodically updated and checked for consistency, see 2.2.5.3.

2.4.5.4 New application fields

With rapidly changing technologies, there is a great need for all kinds of hybrid LCA approaches, including the advanced and input-output analysis-based LCA models. Even in areas for which hybrid LCAs have already been carried out (e.g., office buildings, electricity generation), there is a need to constantly update and actualize the models as well as the results. This can only be done with formalized and practical hybrid LCA models.

The fields of application of hybrid LCA are expanding in number along with the expansion of applications in EIO-LCA, see 2.2.5.4.

2.5 Characterisation of EMC

The basis for the development of the "Environmentally Weighted Material consumption" (EMC) was the need for a tool which could measure and monitor the decoupling of economic growth and resource consumption. The EMC results might be used to measure differences between countries or - probably more importantly - the ecological development of a country over time.

EMC is a hybrid approach linking the LCA method to MFA. Material flows are to be connected with environmental impacts taken from life cycle impacts. Thereby not only the materials themselves are considered but also all other impacts caused during their life cycle (due to extraction of raw materials, production, use and waste disposal). The calculated impacts per mass are attributed to each material; the sum of all impacts over all materials consumed nationwide reveals the environmental impact of a nation's material consumption.

2.5.1 Methodological description

In order to discern the environmental impacts over the life cycle of the consumption of materials two information are needed: the life-cycle impact per mass (a notional functional unit of 1 kg is applied) and the mass which is actually consumed. For the impacts per mass existing LCA software and databases are used. Information about the amount of materials consumed is taken from material flow accounts; namely the indicator DMC is used in the method. The DMC reveals domestic consumption by taking into account all domestic material extractions and the import of materials (exports are deducted). While DMC considers materials at a resource level for the EMC the definition of materials changes somewhat. In order to avoid raw materials which might not have the most environmental relevance the EMC defines materials at the level of "finished" materials, a step before actual products.

Impacts caused by waste treatment and the use of the material are included in the method while impacts directly caused by the product during consumption are by definition excluded.

In the approach taken in the initial development of EMC, the result was given as single-score. No weighting was applied; the results for different impact categories were simply added after normalising them with reference to world impact (which might actually be viewed as weighting based on mass). This is not caused by the method itself though; a multi-score result is also possible, as are different weighting approaches [69].

Included impact categories are:

- Abiotic Depletion Potential (kg antimony equivalents)

- Land Competition (m^2.year)

- Global Warming Potentials (kg CO_2 equivalents)

- Ozone Depletion Potential (kg CFC-11 equivalents)

- Human Toxicity Potential (kg 1,4 dichlorobenzene equivalents)

- Freshwater Aquatic Ecosystem Toxicity Potential (kg 1,4 dichlorobenzene equivalents)

- Terrestrial Ecosystem Toxicity Potential (kg 1,4 dichlorobenzene equivalents)

- Photochemical Oxidant Creation Potential (kg ethylene equivalent)

- Acidification Potential (kg SO_2 equivalent)

- Eutrophication Potential (kg PO_4 equivalent)

- Radiation (DALY)

- Final solid waste (kg / kg)

2.5.2   Development of the EMC

2.5.2.1   History

It has been tried to measure decoupling by applying the Domestic Material Consumption (DMC), derived from national MFA accounts, over economic unit [36]. However, the approach entirely neglects the difference in environmental impacts of different materials. This attempt at decoupling can be seen as a basis for the development of EMC which was first introduced in 2005. Other than that there is no historic account of the EMC.

2.5.2.2   Recent developments

The EMC method as described here was developed by the Institute of Environmental Sciences (CML) of University Leiden, CE Delft and Wuppertal Institute within the EU Thematic Strategy on the Sustainable Use of Natural Resources in 2005 [69]. EMC has been suggested for inclusion in a basket of indicators for measuring the negative environmental impacts related to EU resource use [70].

2.5.3   Major applications of EMC

Conducted only on research basis for the (in 2005) 25 EU and the three candidate (at that time: Bulgaria, Romania and Turkey) countries; considering 32 base materials [69].

2.5.4   Identified gaps in the method

2.5.4.1   Methodological gaps

DMC system boundaries are used for the EMC method. This means that no internal flows are taken into account and it is constituted of domestically extracted materials (minus exports) and imports. Therefore production in a strict sense (which would also include secondary production from waste materials) and recycling within the respective economy are neglected. They can only be discerned indirectly due to a

decrease in the extraction of primary materials or a decrease in imports [36]. EMC combines national material flows and environmental impacts derived from LCA databases where the regional allocation is a different one. The original EMC study used impact data for Western Europe which was not necessarily appropriate for all considered countries. If the method is used for monitoring, development will more likely be shown by the amount of material flows than by any technological improvement.

The EMC aims at a single score result. In order to achieve that the normalised impact results are added up; no actual weighting is applied. While thereby avoiding any dispute on the weighting system the approach can easily lead to an underestimation of highly relevant environmental burden. As in LCA there is also the problem of scientific soundness of the assessment, especially in some impact categories. There is also the risk of double counting due to the inclusion of one material in another which needs to be avoided.

2.5.4.2   Data gaps

Data basis for EMC are national material flow accounts. Therefore the method is only applicable where those exist. For many countries especially developing countries these accounts are not available. For the EU-27 data on DMC is publicly available, though [71]. If available, the data may still differ in time, depth and comprehensiveness.

For the impact assessment the results depend on the chosen database (e.g. geographic background, availability of information on studied materials). Also, the age of the data used for the impact assessment may differ from the age of material flow accounts since it is not updated as continuously.

2.5.4.3   Necessary future research

Future research needs to address the identified problems in the selection of system boundaries and the conformance of MFA and LCA data. The applicability of impact data for timelines needs to be improved.

Best et al. (2008) state that EMC needs improvement with regard to the calculation of the amounts of different materials consumed in a national economy. The transparency and quality of the impact factors should also be improved.[70]

2.5.5   Methodological research

2.5.5.1   Ongoing development work

None discernible.

2.5.5.2   Foreseen development work

Future research on EMC is not foreseeable at the moment.

2.5.5.3   Improvement in data basis

The necessary improvements in data are connected to the two main data sets used for the EMC: the material flow data and the impact data. MFA data should be made available by more countries. The LCA data would be of more benefit if a) more materials were included and b) it was updated more regularly which would make time series possible and therefore monitoring accomplishable. If the objective of applying EMC is a comparison between different countries, country specific LCA data is necessary.

2.5.5.4   New application fields

The EMC has been carried out exemplarily for European countries. The application could be regionally expanded.

3 Development of an Evaluation Scheme

The applicability and appropriateness of the life cycle methods shall be determined for the different levels of decision making. 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 evaluation uses a quantitative scoring, applying a scoring system consisting of different sub-criteria sufficiently defining each criterion. Due to the number of criteria more advanced multi-attribute-decision-making methods (e.g. AHP) are not applied. Instead each aspect of the various criteria scores on a scale from 0 to 4; ranging from "no compliance" of the method with the aspect to "full compliance", see below.

0	No compliance
1	Low compliance
2	Medium compliance
3	Essential compliance
4	Full compliance

In order to make the scoring more transparent the issues which are considered for each aspect are discussed in this chapter.

The criteria are grouped into four categories: first the general criteria are discussed, followed by the methodological, the technical and the data criteria. A tabular overview of all criteria and relevant sub-criteria is given in Annex 1.

3.1 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.

3.1.1 Method documentation and transparency

The criterion "method documentation and transparency" will be measured using diverse sub-criteria rather than evaluating one very narrow issue, like for example the number of available documentations. The criterion will be subdivided into the following sub-criteria:

- Availability of guidelines or code of conduct

- Detailed expert documentation

- Comprehensible calculation and transparency

- Availability of standardisation for method

For the *availability of publicly available guidelines or a code of conduct* (as e.g. the SETAC code of practice on Life cycle assessment) it is taken into account if such documents are published and accessible, widely accepted and if there are commitments to apply them on different scope levels. The focus here is on the availability of unanimous instructions for the application by providing a widely accepted set of rules defining how the specific life cycle method is to be conducted.

Detailed expert documentation on the other hand is understood as e.g. a textbook exists for the life cycle method giving a detailed and comprehensive description of the method. It should be comprehensible and reviewed but also originate from a reliable source. As for the aspect regarding the existence of a code of conduct it is considered if the documentation is published and accessible. Also, the number of methodological papers found in scientific online databases is used as an indicator for the level of available expert documentation. Namely the database ISI Web of Knowledge - Web of Science is considered. The database covers about 9300 scientific journals from different fields and therefore provides ample information for this aspect. As described in the introduction no quantitative threshold will be set but rather the scores will be allocated to the methods in a relative way.

A comprehensible calculation and an overall transparency can be achieved by allowing access to the basic data in a calculation and also by its detailed documentation. Accessibility to the basic data means that the method allows the originally collected data to be accessible for review, at least under confidentiality. If a functional model is used dependencies and relations are more obvious.

The availability of a standardisation is measured according to the level of existing standardisation from "in preparation" to "international standardisation available".

3.1.2   Applicability

The life cycle methods should preferably be applicable as broadly as possible. Hence, wide-spread application areas are taken as measures for this criterion. The criterion is expected to be important in distinguishing between the different scope situations.

It will be considered if the method can be applied for:

- A broad range of goods and services

- A broad range of tasks

The applicability for a *broad range of goods and services* targets the range of possible different objects which might be studied by a life cycle method. It considers all stages of the value chain (consumer goods, intermediate goods, etc.) as well as if it can be used for goods only or for both, goods and services. Also relevant for the sub-criterion is the flexibility of the method to adjustments in systems definition (depending on goal and scope of the study).

The sub-criterion *broad range of tasks* covers many different possible tasks from the general aspect of comparing systems to specific marketing or communication applications. The applicability for marketing and communication entails that the results of the life cycle method can deliver a basis for e.g. eco-labelling or other easily communicable tools with the goal of promoting environmentally desirable products or processes. Marketing is usually associated with the promotion and selling of a product as well as market research. For the purpose of the study, marketing on the political level will be understood as e.g. campaigns for greener products. The sub-criterion evaluates in which detail changes can be analysed, if drivers can be identified and traced and if cause-effect-chains can be identified for improvement analyses. On the micro level improvement analyses mainly address the improvement of single products of the same function. On the macro level, improvement analyses include identifying weaknesses or risks and the deduction of potential changes in e.g. the implementation of new national and EU policies. Furthermore the level of improvement (single products/type of product/sector/region) as well as the possibility to deduce potential changes (including on policy level) and to identify risks contribute to the score in this sub-criterion.

3.1.3   Stakeholder acceptance

The degree of acceptance of the method by the stakeholder is influenced by two main issues one of which is subdivided further. Stakeholder acceptance is determined by the following sub-criteria:

- Inclusion of stakeholders

- Method application by green and consumer NGOs

- Method application by industry

- Method application by policy makers

Firstly, stakeholder acceptance increases if the stakeholders are *included* in the *development of the method* but also in the *decision making process*. Including stakeholders could either be done by active participation but also by enabling and accepting stakeholder reviews.

For the sub-criterion *inclusion of stakeholders* it is considered if stakeholders were included in the development of the method (i.e. was there any involvement at all, did

it lead to binding or only informal feedback?) since this increases acceptance. It is also considered if stakeholders are included in the decision making, i.e. if such an inclusion is an integral part of the method. A further aspect of acceptance is the equal and unbiased treatment of different stakeholder groups and interests.

Secondly the acceptance can be derived from the number of societal parties which apply the method. Therefore it will be analysed if *industry* as well as *policy makers* as well as *NGOs* make use of the method. This choice of stakeholders covers all central stakeholder groups since consumers or the public at large - who one could argue need to be addressed as well - are subsumed under NGOs. 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; otherwise they would not have been chosen for this study.

The *application by NGOs* is measured by the range of application regarding scope and the range of uses to which the results of the method are put (e.g. publication, information of public, legislative proposals, exerting pressure on industry, policy).

For the sub-criterion of *application by industry* the level of utilization by companies and by industry sectors as well as the availability of voluntary commitments are considered.

The sub-criterion of *policy makers' application* takes into account the level of policy decision (i.e. international, national or sub-national), the type of policy (e.g. regulatory policies, directives, voluntary policies or background study/support to policy development), the number of policies issued and also the number of countries applying the method on policy level.

The sub-criteria for stakeholder acceptance are connected to the ones chosen to measure the applicability of the method but the focus of the two criteria is different. The criterion for broad applicability places more emphasis on potential applications while the criterion for stakeholder acceptance aims to measure the actual application.

3.1.4   Objectivity in application

Objectivity is a measure for the independence of the result regarding the user and its reproducibility while the influence of assumptions gives evidence on the independence of the result from both external and internal influences. These sub-criteria are therefore evaluated here:

- Reproducibility

- Influence of assumptions

Reproducibility can be assumed if the results depend neither on the user applying the method nor on the repetition of the application. The first aspect does not only take into account the dependence of the results on choices to be made by the user but

also if restrictions occur in the application due to different user groups or variations, e.g. geographical or temporal. To measure the *influence of assumptions* it is considered if the extent of value choices as part of the method, e.g. method-implicit assumptions on data and their aggregation, is low. If value choices are necessary they should be clearly stated. In order to obtain the extent of the influence, uncertainty analyses should be applied for quantification.

3.1.5   Communicability of method

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

- Clarity of method

- Established communication

The first sub-criterion of communicability is already partly addressed by the criterion method documentation and transparency. Nevertheless it will be included here as well since the availability of a comprehensive documentation enhances the *clarity of a method* and therefore its communicability. If the basic concept is simple, the relation between the steps of the method is comprehensible and connections are logical and transparent, the method can be explained straightforwardly. Even though neither the application nor the results necessarily have to be simple, they should be unambiguous to improve the general willingness to get acquainted with and accept the method.

The history and the level of awareness are of influence to the communicability of a method and therefore also to its results. The level of awareness can be measured by the existence of an established communication: Are there already *established tools for communication* (e.g. ISO type III EPDs) and previous communication which can be consulted for support? Are there previous examples of communication which can be consulted? If so, on which level did they take place, what were their goals and how successful were they? How well can the way of communication be adapted to the needs of different target audiences?

The aspect takes into account if communication tools exist and are applied, contrary to the criterion for broad applicability which considers the potential of the life cycle method to serve as a basis for communication tools.

3.2   Methodological criteria

The two methodological criteria are applied in order to assess the robustness and completeness of the life cycle methods. They concern the question if the methods' principles and procedures are appropriately defined.

3.2.1   Scientific soundness

Scientific soundness is one of the most important criteria in order to achieve dependability and balance of the result. The three sub-criteria used here for distinction are:

- Scientific societies exist

- Validation/ verification checks

- Plausibility of results

For this study more general aspects of scientific soundness such as validity and reliability are not chosen since they are not measurable directly here. These issues will rather be evaluated indirectly by sub-criteria more specific to the problem.

It will be considered if *scientific societies exist* which are concerned with the respective methods and how well they promote research on their topic. This can be done on national or international level and is a mean to cover regional differences. Scientific societies are generally a measure for the scientific discussion on the methods which in itself supports the improvement of scientific soundness.

If the method asks for *validation or verification checks* which ensure the accuracy of the result, e.g. *checks for consistency, completeness, sensitivity, errors, etc.* the scientific soundness can also be enhanced. Not all of these checks need to be applied but some checks for accuracy should be mandatory in the methodology itself. Results can also be consolidated by a validation of the disaggregated results against measured environmental data; therefore it is evaluated if such a disaggregation is possible for the method. If critical reviews according to the ISO 14040 and 14044 standards are part of the method results can be assumed to be more reliable. Independent peer reviews enhance the validity of results as well but with less significance.

Plausibility of results as necessary for this study can be revealed by analysing if a strong link between the used data and the results exists in general and if there is a scientific correlation between the used data and the environmental assessment. Environmental effects should also be measured directly. A strong link between data and results is understood as follows: If the data is processed (e.g. collected and aggregated) from the beginning with the same intention as its application, the amount of necessary adaptations is limited. Adaptation needs increase when using data that was not originally collected or aggregated for the method in question or a similar application, e.g. when using data for environmental assessment that was collected for accountancy. This does not necessarily have to lead to incorrect results but is expected to impede the traceability and thereby plausibility of the result.

3.2.2 Methodological completeness

Methodological completeness is achieved if procedures regarding all important aspects of the method exist. The considered sub-criteria are therefore:

- Method is defined for system boundary

- Method is defined for multifunctional situations

- Method is suitable for comprehensive environmental assessment

At the same time, for the purpose of this study the method needs to:

- Enables analysis of whole life cycle

Though there are more procedural definitions necessary for the application of the methods, these three are essential for all studied life cycle methods while others may only be applicable for certain methods. The procedural issue of data quality, which is also generally applicable for the studied life cycle methods, is covered by a separate criterion and therefore excluded from this criterion so as to avoid double counting.

The *system boundary* defines the physical outline of the studied system by applying certain criteria concerning the stages, processes, and flows to be included, thereby fulfilling one prerequisite for any intended comparison. This aspect also covers the issue of cut-off criteria.

The occurrence of *multifunctional situations* can alter the result of a study significantly. Since it is rarely unnecessary when dealing with industrial processes, it will be evaluated if the methodology requires a procedure for dealing with these situations.

Unlike the previous two sub-criteria, *impact assessment* does not include all phases of the methods. Its importance is emphasised by the environmental focus of the study. The methodological requirement to define procedures for the impact assessment, including the selection and modelling of impact categories appropriate for the studied question, will therefore be evaluated as well. A comprehensive impact assessment should result in a differentiated, comprehensive picture of the impact situation, covering natural resources, human health and ecosystem quality.

The assessment of environmental impacts over the *whole life cycle* of the studied problem is a prerequisite to this study. The method itself can therefore only be complete if it also targets *the entire life cycle*.

3.3 Technical criteria

Technical criteria encompass issues related to the practical application of the method (except data issues which are discussed in the following chapter). The difference to the general criteria lies in the focus of the assessed criteria, even

though the general criteria include applicability. The criterion "broad applicability" is able to point out the usability of a method for different objectives while the technical criteria provide an indication of the manageability and effort of method application.

3.3.1   Availability of software tools

For the evaluation of the software availability, the sub-criteria are:

- Number of available tools

- Variation in licence models

Concerning the first sub-criterion, it is differentiated between the availability of *expert and simplified tools* for each method. A simplified tool is defined as a tool which covers all necessary features and is able to conduct an entire study with the respective method but leaves the user with only very limited adaptation options, e.g. in choosing the assessment method or changing parameters in order to conduct a sensitivity analysis. An expert tool on the other hand allows for more of this kind of independence.

But the number of tools alone is not adequately significant; therefore the *variation in the license model* will be considered and determined if there are *both freely and commercially distributed* tools. Each available license model contributes to the score in the evaluating system since a greater variety is considered beneficial in terms of easing access to different user groups via free license tools e.g. for academic users; and ensuring long-term supported tools with better user-interfaces, available service support, etc. via the commercial license tools mainly used in the private sector.

3.3.2   Suitability for time specific models

Suitability for time dependent models will be divided into considerations on:

- Time series

- Future scenarios

Significant information can only be achieved by a *time series* if the data is updated in appropriate intervals and the time lag between data collection and provision is low. The interval between updates may not be larger than the lag between the single points in the time series, e.g. one year, i.e. data that represents an annual time frame can be modelled each year (provision of databases may take longer, the aspect is concerned with the collection and processing of the data itself). The commitment of the data supplier to keep updating the data or the existence of incentives, e.g. via legal instruments or financial incentives such as licensing, are crucial indicators for a regular data update. But even if the update intervals are adequate, the data still needs to be provided so it can be used for the modelling. If the lag between collection

and provision is large, the modelling of time series will bear little relation to reality and the conclusions drawn from them may be outdated before they are actually drawn. The targeted time is 12 months. The continuous or repeated application of the method supports the development of time series. It is facilitated if already intended by the methodology itself which will therefore be also considered as an important aspect. If a time series is not able to reflect only the true changes in environmental performance adequately, but is distorted/influenced by other factors or can not capture important changes, its use is very limited.

In order to be suitable for the modelling of *future scenarios* a method needs to be able to distinguish and indicate the consequences of relevant measures or other changes that lead to variations in the overall environmental impact. Therefore data which are able to reflect these consequences need to be used and the structures or subsystems relevant for changes need to be identified. Data needs to be adaptable to time focused evaluations and needs to have good potential to be developed further. The main question here is if the consequences of decisions can be concluded based on the application of the method and data used. The more specific scenarios can be modelled (e.g. for technologies vs. sectors), the more reliable they can be, as they are able to capture different influence factors. If reliable and robust future scenarios are to be developed the *reliability of the estimated data* is of great importance. Different factors contribute to the certainty or uncertainty of data and will be considered. Both the methods, the parameters used for the future scenarios, and the underlying data/models play a role. Important is a limited uncertainty in the models. Even though the availability of software tools is a separate criterion, the availability of a tool including certain features is a strong indicator of the feasibility of future scenarios. To model future scenarios the analysis of significant parameters and their variation is imperative and hardly possible with justifiable effort without an proper software tool. If the time itself is variable it seems likely that the modelling of time dependent scenarios is intrinsic to the method. The suitability of a method to model future scenarios is therefore enhanced by the inclusion of time as a variable.

3.4   Data criteria

Data criteria take into account important issues connected with data provision as well as quality requirements. Some of these issues can hardly be considered irrespective of a specific case study (especially data quality) which is why they had to be introduced indirectly.

3.4.1   Data availability and accessibility

The data criteria for availability and accessibility are joined and evaluated as one criterion since both are influenced by the same sub-criteria. As being of the highest importance the following sub-criteria are considered:

- Data coverage of the whole life cycle

- Availability of inventory data for different regions

- Availability of inventory data for all relevant impact categories

- Publicly accessible inventory databases at affordable cost

It will be evaluated if is theoretically possible to provide complete *data for all life cycle stages*, i.e. raw material acquisition, production, disposal, etc.

Regional data availability is relevant if the data is regionally different, e.g. due to different state-of-the-arts in technologies and different emission factors. Data should then be available for different continents, different industrial and trade areas or alternatively be adaptable to different conditions.

In order to conduct a complete impact assessment background data for all relevant *impact categories* needs to be available, e.g. for global warming, acidification, human toxicity, ozone layer depletion, eutrophication.

Databases do not have to be cost-free in order to be considered *publicly accessible* (though it is assumed necessary that the cost is not prohibitively high) and can therefore be available on a free, non-profit or commercial basis. Variety is viewed as beneficial. The charged amount play a dominant role in the cost for calculating the indicators, considering the total cost for developing the indicators for a ten years time series.

3.4.2   Data quality

The sub-criteria defining data quality are as follows:

- Data characteristics

- Independent review

- Data representativeness

- Data documentation

Data quality cannot be evaluated directly since it is highly dependent on the specific situation, i.e. data quality aspects such as representativeness, consistency or precision highly depend on the specific application and cannot be evaluated on a general method level. With regard to its importance though, it will be evaluated within this scheme if certain measures to ensure data quality are implied in the method and also if an appropriate data quality can be achieved theoretically.

Data characteristics contribute to the quality if economic and environmental information is independent and the originally intended level of resolution (micro- or macro-level) is consistent with the level of application. The independence of

economic and environmental information is a condition precedent to the meaningfulness of the environmental indicator and in addition for the development of a meaningful eco-efficiency indicator.

*Independent review*s should be conducted to ensure data quality. They can be done internally or by a third party but defined by specific procedures.

Data representativeness evaluates how far the data sets available for the method are able to characterize the system under analysis in terms of technology coverage, time span, type of measurement and source. The sub-criterion is expected to deliver a differentiated picture for the micro and macro level.

If data quality, especially the characteristics, is *documented*, background information, which helps to select and apply the appropriate data, is gained. The other aspects defining data quality should also be documented to enhance transparency and comprehensiveness, thereby contributing to quality.

4   Evaluation of the Life Cycle Methods

The evaluation encompasses two scopes: the micro level and the macro level (see Introduction). In addition the long-term potential of each method is evaluated (see chapter 4.2). For this the estimated situation 10 years from now is considered.

The micro perspective is typically connected to decision making related to specific products or product groups. This is applicable both in the business and policy domains. 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. It may similarly want to communicate the environmental performance of a product.

The macro perspective, on the other hand, is linked to policy questions involving e.g. a nation or a broader region like the EU-27 or an entire business sector. For instance, the monitoring of decoupling between economic growth and overall environmental impact of the EU-27 consumption system, as addressed in the thematic strategy on resources, is an important case where a life cycle approach is required. Similarly, life cycle methods can provide beneficial insights in e.g. scenario/impact analysis for policies.

 As said in chapter 1, the ILCD Handbook defines several cases of micro and macro applications where a life cycle approach can be used.

The evaluation is done on the level of sub-criteria; the criteria are used for grouping only. This way unintentional weighting is avoided. Whenever quantitative numbers are evaluated, the methods are evaluated relatively to each other thereby avoiding the need for thresholds, i.e. the scores reveal a gradation of the methods corresponding to the quantitative numbers. The scoring system has been described at the beginning of chapter 3.

The detailed results for the evaluation are shown in Annex 2 – and Table 55.

In addition to the evaluation shown in this chapter a weighting scheme was adopted to highlight specific criteria and check their impact on the overall evaluation. The weighting scheme can be found in Annex 3 and the weighted results in Annex 4 and 5.

4.1 Evaluation of the present situation

4.1.1 General criteria

4.1.1.1 Method documentation and transparency

4.1.1.1.1 Guidelines or code of conduct:

P-LCA: Essential compliance on micro and macro level.

Guidelines can be found on both the micro and the macro level, as mentioned there are some on single products, on specific industries but also on a public policy level. Existing guidelines by SETAC were the first to be published in 1993 [5], others - dealing with different aspect of P-LCA e.g. just the inventory or a certain product range - have followed. Especially the SETAC code of practice is widely accepted as basis for application. Comprehensive guidelines applicable for both the micro and the macro level are provided by the ILCD handbook [1, 12, 72-74]. Further examples for macro level guidelines are sectoral guidelines, e.g. of the steel industry [75], the guidelines by the paper industry [76] or the guidelines by the plastics industry regarding groups of polymers [77].

EIO-LCA: Medium compliance on micro and essential compliance on macro level.

There are no guidelines or codes of conduct specifically for EIO-LCA, but the general LCA guidelines and principles are applicable to EIO-LCA as well. In addition guidelines on the macro level can be found for the separated part of economic and environmental accounting as well as guidelines integrating both of these accounting parts [78, 79].

MFA: No compliance on micro level, essential compliance on macro level.

There are no guidelines or similar available for the MFA on the micro-level. On the macro-level however there is a methodological guide for economy-wide material flow accounts published by the European Commission as well as one by the OECD [40, 41].

EMC: No compliance on micro or macro level.

There are no guidelines or similar available for the EMC.

Hybrid-LCA: Medium compliance on micro and macro level.

For the EIO-LCA the general LCA guidelines should be applied and valid since all hybrid approaches are a combination of P-LCA and EIO-LCA. There are no specific guidelines, but the procedural guidelines mentioned for P-LCA are applicable as well.

Table 4:   Quantitative evaluation for sub-criterion "guidelines or code of conduct"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
3	3	2	3	0	3	0	0	2	2

4.1.1.1.2 Detailed expert documentation

The aspect of methodological papers on a scientific database is evaluated relatively between the methods since absolute numbers are of low validity. The relative score is used to enhance the results obtained from the other aspects. Despite some uncertainties the search on the scientific database "Web of Science" [80] reveals some tendencies. The majority of papers address P-LCA, followed by papers on EIO-LCA. The work on the MFA methodology is revealed to be less extensive, the work on LCA hybrid methods is far less extensive and the work on EMC basically non-existent.

P-LCA: Complete compliance on micro and and medium compliance on macro level.

The Handbook on LCA by Guinée [81] contributes to a detailed documentation. Furthermore 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 [82]. The expert communication is extensive, given by reliable and also accessible sources. In addition, the Journal Environmental Science and Technology (one of the top-ranked environmental journals in the world) and the Journal of Industrial Ecology have been publishing P-LCA papers regularly.

EIO-LCA: Compliance in essential parts on micro and complete on macro level.

The complete textbook on EIO-LCA, describing the methodology and case studies is given by reference [17]. 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) [65]. 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 macro, i.e. sector-wide applications than on micro or single-product applications.

MFA: Medium compliance on micro level, complete compliance on macro level.

Extensive textbook is available. 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. Focus is mainly on macro level.

EMC: Low compliance on micro and macro level.

As of yet the only methodological work and publication available is the report of the project in which the method was developed. It therefore still lacks an extensive expert documentation. There is no difference between micro and macro level applications.

Hybrid-LCA: Medium compliance on micro and macro level.

The method is documented alongside EIO-LCA and P-LCA, but usually not exclusively. Documentation is available, but is not comprehensive. There is no distinguishable difference between micro and macro studies.

Table 5:   Quantitative evaluation for sub-criterion "detailed expert communication"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
4	2	3	4	2	4	1	1	2	2

4.1.1.1.3 Comprehensible calculation and transparency

P-LCA: Complete compliance on micro level, medium compliance on macro level.

In part dependent on database and its aggregation, but basic data is usually accessible. Transparency is prerequisite and a principle, therefore also in data and relations. E.g. in impact assessment the use of accredited and published characterization models is mandatory. Even though the high complexity, amount of data etc. may reduce the transparency and comprehensibility when the method is applied, on a methodological level transparency is provided. The methodological focus of P-LCA is on the micro level. There is no defined way to extrapolate process based data to the macro level, therefore the comprehensibility of the calculation may be limited.

EIO-LCA: Essential compliance on micro level, complete compliance on macro level.

Calculation is well documented. Data is only accessible from a certain level of aggregation, which is a function of economic and environmental data availability, but not a methodological issue. Current practice is considered appropriate and adequate for macro level scope situations, but not for the micro level. Relations in data matrix require a certain economic knowledge, but are otherwise transparent.

MFA: Medium compliance on micro level, complete compliance on macro level.

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 for macro level, though not on micro level. 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. If micro level is understood as a substance related scope as well, relations and dependencies are revealed better.

EMC: Medium compliance on micro level, complete compliance on macro level.

The reasoning for the results in this sub-criterion is the same as for MFA.

Hybrid-LCA: Low compliance on both micro and macro level.

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. Relations and dependencies are customisable in the model, therefore not generally apparent and comprehensible.

Table 6: Quantitative evaluation for sub-criterion "comprehensible calculation and transparency"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
4	2	3	4	2	4	2	4	1	1

4.1.1.1.4 Availability of standardisation for method

P-LCA: Complete compliance on micro level, medium compliance on macro level

International standardisation that is focused on micro level is available [2, 7]. Specifications on up-scaling from micro-level data to macro-level topics are not available but theoretically the standard is valid for macro level applications as well.

EIO-LCA: Low compliance on micro or macro level.

The ISO standards 14040 and 14044 aim to model the product system by using physical (material or energy) flows [2, 7]. EIO-LCA uses a monetary representation of these flows, but most of the time it starts the LCA of a product or service with a physical notion of the problem, which then needs to be converted into a monetary unit. Thus, the current 14040 and 14044 standards apply in principle. At the moment there are no efforts to specifically standardise EIO-LCA.

MFA: No compliance on micro or macro level.

There is no standardisation available at the moment.

EMC: No compliance on micro or macro level.

There is no standardisation available at the moment.

Hybrid-LCA: Medium compliance on both micro and macro level.

In contrast to the "pure" EIO-LCA, the hybrid approaches may be compliant with the ISO 14040 and 14044 if the ISO requirements, especially concerning the impact assessment, are fulfilled. Compliance here is therefore case dependent. However, since monetary flows are used at least partially, they will not be fully compliant with ISO.

Table 7:   **Quantitative evaluation for sub-criterion "availability of standardisation"**

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
4	2	1	1	0	0	0	0	2	2

4.1.1.2   Applicability

4.1.1.2.1 Broad range of goods and services

P-LCA: Complete compliance on both micro and macro level.

Method is applicable to a wide range of goods and services in all phases of value chain and can be easily adjusted to individual needs. From a methodological point of view there is no restriction on micro level. On macro level possible restrictions are due to lack of completeness in the method description (e.g. transfer from micro processes to macro scale) and will be evaluated there.

EIO-LCA: Essential compliance on micro and macro level.

The method is directly applicable to all goods and services in an economy, created by private or government entities. Coverage and range are by method design complete (because the I-O tables serve to calculate the Gross Domestic Product or a regional equivalent), but detail of input-output tables varies from economy to economy. However, this is not a methodological limitation but a practical one (how much data are collected for a region's input-output tables). The analysis is currently typically sector-specific or product-group-specific, and varies from economy to economy. Flexibility of the basic method for a given year of analysis is low, but system definitions (e.g., different products with different inputs and outputs) may change from year to year, so flexibility comes from updates to the economic and environmental data in EIO-LCA, which are periodic and regular. The rating is less than complete because of the lack of flexibility.

MFA: Medium compliance on both micro and macro level.

On a substance/material level applicability is not limited, system can be adjusted. However, due to focus on materials, application for services has not been of interest so far. Application along the value chain is limited.

EMC: Medium compliance on both micro and macro level.

No difference to MFA is discernible.

Hybrid-LCA: Complete compliance on both micro and macro level.

High flexibility in combination of EIO-LCA and P-LCA parts, the flexibility of adjustments in systems definition is also very high and the possible applications are not limited.

Table 8:   Quantitative evaluation for sub-criterion "broad range of goods and services"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
4	4	3	3	2	2	2	2	4	4

4.1.1.2.2 Broad range of tasks

P-LCA: Complete compliance on micro level, compliance in essential parts on macro level.

Systems can be compared on both micro and macro level. Improvement analysis is an important application of the method on different levels. However, on macro level the identification of cause-effect chains and tracing of drivers and thereby the deduction of potential changes is limited due to the necessary aggregation. Marketing applications are possible.

EIO-LCA: Medium compliance on micro level, essential compliance macro level.

Systems can be compared by the method and an improvement analysis conducted. On the macro level this is only limited by the level of detail which may interfere with analyses of e.g. products. On the micro level necessary disaggregation may reduce the significance of the results. Marketing applications are possible.

MFA: Low compliance on micro level, medium compliance on macro level.

Improvement analysis is an important application of MFA, especially by the identification and tracing of drivers. Limitations occur due to the methodological focus on regions; this is especially apparent on the micro level. The comparison of systems is not intended; marketing applications not feasible. Potential changes are not discernable by the method.

EMC: Low compliance on micro level, essential compliance on macro level.

The possible applications of EMC are widely comparable to the MFA ones, though there is improvement on the macro level. Due to the added environmental assessment, cause-effect chains can be identified more easily and the marketing applications improve.

Hybrid-LCA: Complete compliance on macro and micro level.

A broad range of tasks is possible on the macro level, but with the EIO-LCA's limiting factors. On the micro level there is a broad applicability because of the use of P-LCA as the front method (direct emissions with a few suppliers) and EIO-LCA as the supply chain mapping method.

Table 9: Quantitative evaluation for sub-criterion "broad range of tasks"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
4	3	2	3	1	2	1	3	4	4

4.1.1.3   Stakeholder acceptance

4.1.1.3.1 Inclusion of stakeholders

P-LCA: Compliance in essential parts on both micro and macro level.

The process of standardisation by ISO takes into account the views of major stakeholder groups such as consumer, research, political and industry groups and therefore stakeholders were included during the development of P-LCA [83]. The interests are treated fairly. Inclusion in the decision making is not stipulated. No difference can be distinguished between micro and macro level here.

EIO-LCA: Low compliance on both micro and macro level.

There is no unfair treatment of different stakeholder groups as such, but the distribution of sectors may lead to systematic over- or underestimation of certain industry groups. The stakeholders have not been engaged in the development of the method.

MFA: Low compliance on micro and medium macro level.

Due to the focus on substances/materials there is no unequal treatment of different stakeholders implicit in the method. Some material flows are easier to trace and have therefore been analyzed more, but this is a problem of data not bias. The other aspects to be considered here are not fulfilled.

EMC: Medium compliance on both micro and macro level.

When the EMC method was developed a group of experts from different stakeholder groups was invited to discuss the new methodology [84]. Even though this was an expert discussion, this is still viewed as stakeholder inclusion. Bias against certain stakeholder groups is not discernible.

Hybrid-LCA: Medium compliance on both micro and macro level.

There is no unfair treatment or favouritism of different stakeholder groups. But the stakeholders have not been engaged in the development of the EIO-LCA method. However, there is essential compliance when Hybrid LCA uses P-LCA for micro and macro applications as front-end analysis, with EIO-LCA aiding supply chain analysis. Overall, we rated hybrid LCA as having only medium compliance because of the possibility of EIO-LCA being dominant in the analysis, and for which compliance is currently low.

Table 10: Quantitative evaluation for sub-criterion "inclusion of stakeholders"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
3	3	1	1	1	2	2	2	2	2

4.1.1.3.2 Method application by green and consumer NGOs

The evaluation of this sub-criterion showed that there are no significant applications of any of the regarded methods by NGOs. The sub-criterion will therefore be removed from the evaluation.

4.1.1.3.3 Method application by industry

P-LCA: Complete compliance on and low compliance on macro level.

P-LCA is applied by industry on a regular basis, the applications conducted by industry associations are viewed as macro applications, but there are few. Voluntary commitments exist on the micro level.

EIO-LCA: Low compliance on micro and macro level.

The industry application of EIO-LCA is not as regular on the micro level as that of P-LCA, but relevant statistics are not collected. The assessment here is therefore based on personal experience. To our knowledge, industry groups, such as trade organizations, have not applied EIO-LCA.

MFA: Low compliance on micro level, compliance in essential parts on macro level.

On the micro level the direct implementation of MFA in industries seems limited. The reason for this, however, could be that there have been so far few implementations of MFA by industries or because they have made it confidential. Most of the big companies have identified the total inputs and outputs to and from the companies in a year. MFA is applied on sector wide issues on the macro level. No commitments to apply the method could be found.

EMC: No compliance on micro or macro level.

There is no application by industry.

Hybrid-LCA: Low compliance on micro level, no compliance on macro level.

There is sparse application by industry, but usage statistics are not collected. This assessment is based on personal experience.

Table 11:   Quantitative evaluation for sub-criterion "method application by industry"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
4	1	1	1	1	3	0	0	1	0

4.1.1.3.4 Method application by policy makers

P-LCA: Complete compliance on both micro and macro level.

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 [85, 86]. According to Schenck (2009) LCA has widely been used as the basis for policy making in the US [87].

EIO-LCA: No compliance on micro level, complete compliance on macro level.

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 comprehensive life-cycle study of retail products will be used for informing carbon labelling policy (see [88]). 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 [32, 89].

MFA: No compliance on micro level, complete compliance on macro level.

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, i.e. total inputs and outputs to and from Japan in a year, for many years. 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.

EMC: No compliance on micro or macro level.

There is currently no application by policy makers.

Hybrid-LCA: No compliance on micro or macro level.

There is no application by policy makers.

Table 12:   Quantitative evaluation for sub-criterion "method application by policy makers"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
4	**4**	**0**	**4**	**0**	**4**	**0**	**0**	**0**	**0**

4.1.1.4   Objectivity in application

4.1.1.4.1 Reproducibility

P-LCA: Essential compliance on micro and macro level.

High level of flexibility as with the P-LCA may reduce reproducibility. If goal and scope of a study as well as the approach itself are clearly defined, however, which is necessary if following the ISO principles, the flexibility will be compensated somewhat, though reproducibility is not entirely certain. The same user is more likely to achieve the same result when applying the method repeatedly than different users.

EIO-LCA: Complete compliance on micro and macro level.

With the evaluated aspects regarding repetition of application and independence from user applying the method the compliance of EIO-LCA with this sub-criterion is considered complete.

MFA: Essential compliance on micro and macro level.

As with P-LCA, there are different approaches to apply the method which reduces reproducibility. However, in contrast to P-LCA, there is no standard demanding documentation of adaptations etc. At the same time there are fewer possibilities for methodological variations in MFA.

EMC: Essential compliance on micro and macro level.

In comparison to the MFA, EMC adds an environmental assessment but this does not significantly change the probability of reproducibility since the approach to do that is well defined.

Hybrid-LCA: Essential compliance on micro and macro level.

The use of P-LCA in the hybrid analysis could limit the reproducibility of the results compared to a pure EIO-LCA. The same scores of P-LCA are therefore assigned.

Table 13: Quantitative evaluation for sub-criterion "reproducibility"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
3	3	4	4	3	3	3	3	3	3

4.1.1.4.2 Influence of assumptions

P-LCA: Essential compliance on micro and macro level.

Focus on scientific relations is stated clearly in method description. Value choices occur in the course of the method regarding, e.g., data or choice of impact assessment. They are, however, clearly documented. Uncertainty analyses are possible, but the methods are not prescribed.

EIO-LCA: Medium compliance on micro and macro level.

Value choices may occur before method is applied, for example, due to base year of analysis, but the assumptions are clearly documented. Value choices are implicit in input-output tables as well as 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.

MFA: Essential compliance on micro and macro level.

Value choices are of importance mainly in the identification of the relevant flows and processes which are to be considered. Data of different aggregation levels is used which implies that their quality is comparable and the different levels can be transferred into each other. The problem of uncertainty is addressed but not necessarily quantified.

EMC: Essential compliance on micro and macro level.

The reasoning for the results in this sub-criterion is the same as for MFA.

Hybrid-LCA: Essential compliance on micro and medium compliance on macro level.

The method lays out ways to combine P-LCA and EIO-LCA, thus Hybrid-LCA carries with it the inherent assumptions and value choices of the participating methods. Uncertainty may be reduced relative to P-LCA and EIO-LCA used alone, but not yet consistently analysed.

Table 14: Quantitative evaluation for sub-criterion "influence of assumptions"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
3	3	2	2	3	3	3	3	3	2

4.1.1.5   Communicability of methods

4.1.1.5.1 Clarity of method

P-LCA: Compliance in essential parts on micro level, medium compliance on macro level.

The basic concept is simple, phases are clearly described and connections apparent, but domain expertise is needed in applications. Results are not necessarily unambiguous. On macro level clarity is reduced since the extrapolation of process data is neither entirely defined nor easily understood.

EIO-LCA: Low compliance on micro level, essential compliance on macro level.

The basic concept is fairly simple. Connections between method steps are transparent. However, application of method at micro level may require producer price information and always requires finding the correct economic sector to use for analysis, which all requires non-trivial expertise. Macro level analyses are straightforward.   One disadvantage of the method is that it is not easily comprehensible (connection between I-O tables and environmental impacts, adaptations of tables to the method) to a non-professional audience.

MFA: Medium compliance on micro level, complete compliance on macro level.

Basic concept is simple, especially on macro level. Similar to P-LCA, only instead of product/processes it focuses on materials, system boundary is region. Therefore the method is less simple on the micro level. But it delivers an unambiguous result and features logical connections.

EMC: Medium compliance on micro level, complete compliance on macro level.

Since the basis of EMC is the idea of MFA its concept is fairly simple. The connection between masses as physically defined and environmental impacts is logical.

Hybrid-LCA: Low compliance on micro and macro level.

The method lays out ways to combine P-LCA and EIO-LCA, but is not simple, and requires modelling and domain expertise. However, it can be made transparent (e.g., in scientific publications).

Table 15:   Quantitative evaluation for sub-criterion "clarity of method"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
3	2	1	3	2	4	2	4	1	1

4.1.1.5.2 Established communication

P-LCA: Complete compliance on micro level, medium compliance on macro level.

The method has been used for various fields of communication (e.g., by publication of verified ISO type III EPDs for some relevant goods and services) with regard to the audience and targeted communication type. 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 [90]. 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 [91] for details).

EIO-LCA: Low compliance on micro level, medium compliance on macro level.

The method has been applied and communicated in scientific publications variously on the macro level, and adaptability for different audiences can be assumed. For examples on previous communication see references [88, 92]. On micro level there are few examples of previous communication.

MFA: Low compliance on micro level, compliance in essential parts on macro level.

The method has been used for various fields of communication with regard to the audience and targeted communication type on the macro level. Some companies reported MFA results in their CSR reports, which counts towards previous communication on the micro level (see e.g. [93, 94]).

EMC: No compliance on micro or macro level.

There has been no previous communication.

Hybrid-LCA: No compliance on micro or macro level.

Previous communication is as yet sparse.

Table 16: Quantitative evaluation for sub-criterion "established communication"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	Macro	Micro	Macro	Micro	Macro	Micro	Macro	Micro	Macro
4	2	1	2	1	3	0	0	0	0

4.1.2 Methodological criteria

4.1.2.1 Scientific soundness of the approach

4.1.2.1.1 Existence of Scientific societies

P-LCA: Complete compliance on micro or macro level.

Scientific societies dealing with LCA cover the different approaches.

EIO-LCA: Complete compliance on micro or macro level.

Scientific societies dealing with LCA cover the different approaches.

MFA: Compliance in essential parts on micro or macro level.

Though there is no official scientific society dedicated to MFA, there is something similar to one: the network ConAccount as a platform for MFA practitioners and researcher promotes the development of MFA and the exchange among scientists and institution [95].

EMC: No compliance on micro or macro level.

It is too early in the development state of EMC for any scientific societies to exist.

Hybrid-LCA: Complete compliance on micro or macro level.

Scientific societies concerned with LCA cover the different approaches.

Table 17: Quantitative evaluation for sub-criterion "existence of scientific societies"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	Macro	Micro	Macro	Micro	Macro	Micro	Macro	Micro	Macro
4	4	4	4	3	3	0	0	4	4

4.1.2.1.2 Validation/ verification checks

P-LCA: Complete compliance on micro level, essential compliance on macro level.

Checks, critical reviews and peer reviews are intended; under certain circumstances they are mandatory. Results can be disaggregated completely on micro level, on macro level dependent on available background information.

EIO-LCA: Medium compliance on micro level, essential compliance on macro level.

The method should comply by the same validation checks and expectations as the P-LCA method, but these guidelines are not documented the same way as they are for P-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, and the lower scoring reflects this shortcoming. Disaggregation of results against economic measurements but not against environmental measurements is possible on macro level because the method uses macro level data to start with.

MFA: Medium compliance on micro level, compliance in essential parts on macro level.

Uncertainty and sensitivity checks are intended. Results can be disaggregated on macro level, not on micro level. Peer reviews are not mentioned.

EMC: No compliance on the micro level, low compliance on the macro level.

The problem of uncertainties is addressed, but no actual method to check validity is defined or applied. Results can not be disaggregated on the micro level.

Hybrid-LCA: Medium compliance on micro and essential compliance on macro level.

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 mandatory validation checks and critical review cannot be taken for granted. Disaggregation of results against measurements is possible as per the participating models.

Table 18:   **Quantitative evaluation for sub-criterion "validation/ verification checks"**

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
4	3	2	3	2	3	0	1	2	3

4.1.2.1.3 Plausibility of results

P-LCA: Complete compliance on micro level, medium compliance on macro level.

The methodology requires a clear pathway for allocation of environmental effects to the studied system, but direct measurement of environmental effects (e.g., from a smokestack) is not required. Furthermore, the method requires thorough documentation. 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.

EIO-LCA: Low compliance on micro level, medium compliance on macro level.

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. Typically EIO-LCA economic data availability lags environmental data availability, thus environmental data may be from a more recent year than economic values. While direct measurement of environmental effects (e.g., from a smokestack) is not required, collection and processing of data is consistent with the intention of the results. 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.

MFA: Medium compliance on micro level, essential compliance on macro level.

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.

EMC: Medium compliance on micro level, compliance in essential parts on macro level.

The method as developed and described by the CML gives a single score result. Due to a detailed description of the obtaining of the single score result and the availability of the underlying data the result remains comprehensive. Since semi-manufactured goods are assessed instead of end products, the disaggregation is more reliable than for the EIO-LCA. Correlation between data and environmental assessment is well outlined. On the macro level the used data is consistent with the intended application; on the micro level more adaptations are necessary.

Hybrid-LCA: Essential compliance on both micro and macro level.

The plausibility of the results has the potential to be enhanced relative to the sole use of either EIO-LCA or P-LCA if the procedure for connecting the two methods is carefully executed. For example, 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. The scientific correlation between input data and environmental assessment is dependent on the proportions of the LCA approaches used in an

analysis. Collection and processing of data is consistent with the intention of the results.

Table 19:   **Quantitative evaluation for sub-criterion "plausibility of results"**

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
4	2	1	2	2	3	2	3	3	3

4.1.2.2   Methodological completeness

4.1.2.2.1 Enables analysis of whole life cycle

P-LCA: Complete compliance on both micro and macro level.

All life cycle stages are considered.

EIO-LCA: Medium compliance on both micro and macro level.

Analysis of the entire life cycle is possible, but dependent on sectors included in the input-output matrix and the type of product or service. In general, 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 more realistically. Use phase data can be included if certain additional information is available and applied (e.g., electricity use per household appliance). End of life assessment is difficult. The sub-criterion does not depend on the scope level.

MFA: Complete compliance on both micro and macro level.

All life cycle stages are considered.

EMC: Complete compliance on both micro and macro level.

All life cycle stages are considered.

Hybrid-LCA: Complete compliance on both micro and macro level.

All life cycle stages are considered due to combination of EIO- and P-LCA.

Table 20:   **Quantitative evaluation for sub-criterion "Enables analysis of whole life cycle"**

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
4	4	2	2	4	4	4	4	4	4

4.1.2.2.2 Method is defined for: system boundary

P-LCA: Medium compliance on micro level, low compliance on macro level.

The issue is addressed and a set of requirements to define the system boundary is stated. 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.

EIO-LCA: Medium compliance on micro level, essential compliance on macro level.

The setting of the system boundary is defined and documented clearly. Limitations on all levels occur if the studied product, service, or industry has parts of its value chain outside the boundaries of the I-O tables, which is very common in most developed economies. For example, if components of a product are made in a foreign country, the study of that component has to involve the I-O tables and environmental data of the foreign country. This is currently still a limitation, and the scoring reflects this. Services are less affected by this complication because they are for the most part generated locally. Cut-off criteria are the same as the boundary of the I-O analysis. On the micro level limitations occur if the studied system does not cover the given I-O table because in this case there are no specifications as to how the boundary should be set.

MFA: Low compliance on micro level, complete compliance on macro level.

The system boundary is in part defined by the methodology. The issue is addressed and there are recommendations for setting the boundary. For the macro level the guidelines by EUROSTAT and OECD give a clear path as to how the system boundaries shall be set. [40, 41]

EMC: Low compliance on micro level, complete compliance on macro level.

The setting of the system boundary is described in detail by the methodology on the macro level. The transferability to the micro level is not an issue, it greatly depend on the product in question if the boundaries can be clearly defined.

Hybrid-LCA: Medium compliance on micro and essential compliance on macro level.

Procedures for setting the system boundaries are defined for the contributing methods. On micro level, the expected front-end use of P-LCA suggests a medium compliance, while on macro level the prevalent use of EIO-LCA defines the system boundary clearly and unambiguously, though there is still a rather less defined P-LCA contribution.

Table 21: Quantitative evaluation for sub-criterion "Method is defined for: system boundary"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
2	1	2	3	1	4	1	4	2	3

4.1.2.2.3 Method is defined for: multifunctional situations

This category assesses allocation issues, e.g., when multiple products are produced in the same factory.

P-LCA: Complete compliance on micro level, medium compliance on macro level

Method is defined by an international standard, as described before there is a focus on micro level. Procedures on macro level are less clear.

EIO-LCA: Medium compliance on both micro and macro level.

Though there is not a clearly fixed way for dealing with multi-functional situations in EIO-LCA, there is strong discussion about the different possible ways to address this issue, see for example [96].

MFA: Complete compliance on both micro and macro level.

The focus of the method is usually on single materials 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 problems or difficulties arise from this lack of procedures.

EMC: Complete compliance on micro level, medium compliance on macro level

As the method is a combination between MFA and P-LCA, there are limitations on the macro level, due to the use of LCA data sets to characterize the environmental impacts of material flows.

Hybrid-LCA: Medium compliance on micro and no compliance on macro level.

On micro level the use of P-LCA assures the use of guidance of an international standard, but the combined use with EIO-LCA makes the approach less clear. On macro level the methodology is not defined.

Table 22: Quantitative evaluation for sub-criterion "Method is defined for: multifunctional situations"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
4	2	2	2	4	4	4	2	2	0

4.1.2.2.4 Method is suitable for comprehensive environmental assessment

There is no difference on scope levels here.

P-LCA: Essential compliance on both micro and macro level.

Procedures are defined, considered impact categories shall be appropriate for the goal of the study, but a requirement for categories covering the impact situation entirely is missing. Double counting is addressed.

EIO-LCA: Medium compliance on both micro and macro level.

The handbook [17] states that double counting is addressed and categories which are usually applied cover major aspects of environmental impact assessment. Method is open to include other categories as well. It is necessary, though, to obtain sector-specific emissions data. Some data are incomplete by default since not all companies have to report, for example, their toxic releases (even though the I-O table is not restricted that way, the environmental parameters linked to it are).

MFA: No compliance on both micro and macro level.

Method does not include the impact assessment itself, though it is able to deliver an objective data basis for one.

EMC: Essential compliance on both micro and macro level.

The impact assessment is defined in the methodology including the preferred impact categories (though these are changeable). Even if the method proposes the aggregation of the chosen impact categories to a single score result, the display of individual impact categories contributions is possible.

Hybrid-LCA: Essential compliance on both micro and macro level.

Procedures for selection or handling of possible double counting are not currently available. Impact assessment can be considered essentially complete if P-LCA and EIO-LCA are combined appropriately to studied question.

Table 23: Quantitative evaluation for sub-criterion "Comprehensive environmental assessment"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
3	3	2	2	0	0	3	3	3	3

4.1.3 Technical criteria

4.1.3.1 Availability of software tools

4.1.3.1.1 Number of available tools

P-LCA: Compliance in essential parts on micro level, medium compliance on macro level.

Tools are available on different levels of expertise, region specific applications limited. The focus is on the micro level.

EIO-LCA: Compliance in essential parts on micro level, complete compliance on macro level.

There is a supply of simple-to-use internet tools as well as integration in expert LCA tool (SimaPro). Regional application is possible due to the usually nation-specific database. The focus is on the macro level.

MFA: Complete compliance on micro or macro level.

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. Region specification is possible due to region-related data collection.

EMC: No compliance on micro or macro level.

No software tools as of yet, though calculation uses and combines tools specific for other methods.

Hybrid-LCA: Medium compliance on micro and macro level.

Inclusion in software (SimaPro) exists, but there are no simplified tools. Regional differences partly can be accounted for by EIO-LCA data.

Table 24: Quantitative evaluation for sub-criterion "number of available software tools"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
3	2	3	4	4	4	0	0	2	2

4.1.3.1.2 Variation in licence models

P-LCA: Complete compliance on micro and macro level.

Both free and commercial software tools are available.

EIO-LCA: Complete compliance on micro and macro level.

Both free and commercial software tools are available.

MFA: Complete compliance on micro and macro level.

Both free and commercial software tools are available.

EMC: No compliance on micro and macro level.

There are no software tools yet.

Hybrid-LCA: Medium compliance on micro and macro level.

Only commercial tools are available.

Table 25:　　　Quantitative evaluation for sub-criterion "variation in licence models"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
4	4	4	4	4	4	0	0	2	2

4.1.3.2　Suitability for time specific models

4.1.3.2.1 Time series

P-LCA: Compliance in essential parts on micro, medium compliance on macro level.

For P-LCA data can be updated in appropriate intervals and there is no significant time lag between data collection and data provision in the foreground data. Continuous application is compatible with the methodology and time series are able to reflect true changes in environmental impact. Therefore, P-LCA is suitable for time-dependent models even though it is not yet standard practice today because, e.g., most P-LCA data sets only exist for one point in time for one product from one manufacturer, and most data sets are not regularly updated. As the background data is significant for the macro level especially, only medium compliance can be evaluated here.

EIO-LCA: Essential compliance on micro and macro level

For EIO-LCA the underlying economic data are typically updated every five years, in the EU-27 every one to three years (depending on the kind of table). Another disadvantage is the long time lag between data collection and data provision in the range of several years due to extensive data processing. Continuous application is only possible in the discrete steps of several years. The results of the time series do not necessarily reflect true changes in environmental impact because they might be distorted and influenced by economic or monetary factors. The advantage of EIO-LCA is that the updates are done regularly (but with a time lag), so time series comparisons are enabled.

MFA: Medium compliance on micro level and essential compliance on macro level

For MFA data can be updated in appropriate intervals on micro as well as macro level. For some macro data relying on statistics the time lag between data collection and data provision might be relatively long. For the macro level continuous data is available for various countries, e.g. all EU-27. Continuous application is possible, but hindered due to reliance on trade statistics. It is not intended by the methodology either. The relation of the time series to true changes in environmental impact might be low as there is no direct monitoring of environmental consequences.

EMC: Medium compliance on micro level and essential compliance on macro level

The reasoning for the results in this sub-criterion is the same as for MFA.

Hybrid-LCA: Medium compliance on micro and macro level

For the hybrid methodology, the scoring on the micro level gets better as the use of some P-LCA data allows for quicker updates. However, as long as there is significant use of EIO-LCA based data, some restrictions apply. On macro level, the influence of P-LCA data is expected to reduce the compliance.

Table 26:   Quantitative evaluation for sub-criterion "time series"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	Macro	Micro	Macro	Micro	Macro	Micro	Macro	Micro	Macro
3	2	3	3	2	3	2	3	2	2

4.1.3.2.2 Future scenarios

P-LCA: Compliance in essential parts on micro, medium compliance on macro level.

In P-LCA an analysis of consequences of changes is possible. Due to the process specific models the uncertainty of future impacts can be qualitatively estimated. Data are adaptable to time focused evaluations and have potential to be developed further. Scenario modelling functions and parameterization of time as variable in the functional model are available in several software tools. P-LCA is suitable for future scenarios and they are used at the micro level already. For macro level application of future scenarios P-LCA also depends on statistical data (similarly to EIO-LCA).

EIO-LCA: Low compliance on both micro and macro level.

Due to the model of the past, an analysis of consequences of future changes is not possible systematically in EIO-LCA. The uncertainty of estimated future impacts is therefore high. The data are hardly adaptable to time-focused evaluations, and

scenario modelling functions in the EIO-LCA software are not known. Parameterization, especially for time as variable, is not applicable.

MFA: Low compliance on both micro and macro level.

Like in EIO-LCA also for MFA future scenario modelling is uncommon due to the non-functional, but statistical model of the past, which make an analysis of consequences of future changes impossible. Scenario modelling software and time as parameter are not known.

EMC: Low compliance on both micro and macro level.

The reasoning for this sub-criterion is the same as for MFA.

Hybrid: Medium compliance on both micro and macro level.

For the hybrid methodology, the scoring on the micro level gets better as the use of some P-LCA data may allow for some functional scenario modelling. However, as long as there is significant use of EIO-LCA, some restrictions apply resulting in a medium score for the method.

Table 27: Quantitative evaluation for sub-criterion "future scenarios"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
3	2	1	1	1	1	1	1	2	2

4.1.4   Data criteria

4.1.4.1   Data availability and accessibility

4.1.4.1.1 Data coverage of the whole life cycle

P-LCA: Complete compliance on micro level, medium compliance on macro level.

There are no theoretical limitations in data availability for any life cycle phase. Though in specific applications data may be hard to obtain, this is not a methodological issue, at least not on the micro level. On the macro level however, consistency and reliability of compiling or up-scaling the data is not satisfactorily addressed, which is reflected in the lower scoring of medium compliance.

EIO-LCA: Low compliance on the micro level, essential compliance on the macro level.

The level of detail necessary for disaggregation depends highly on the specific sector in EIO-LCA and is not available for all life cycle phases. Manufacturing and production data from manufacturing industries, agriculture, mining and service

sectors are available. Use-phase analyses are possible for many products (e.g., for which electricity is used), but not for all. The inventory of the whole life cycle can be more easily done on the macro level. End of life data are difficult to obtain on the micro level, but are embedded into macro level applications (e.g., average recycling rates for paper and steel are reflected in those sectors in EIO-LCA).

MFA: Low compliance on micro level, complete compliance on macro level.

The available data for the method is limited on the micro level. On the macro level, especially, in most industrialised countries, the sub-criterion is fulfilled completely since satellite accounts to the System of National Accounts (SNA) provide the necessary data.

EMC: Low compliance on micro level, complete compliance on macro level.

This reasoning for the sub-criterion is the same as for MFA.

Hybrid-LCA: Complete compliance on both micro and macro level.

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 28: **Quantitative evaluation for sub-criterion "data coverage of the whole life cycle"**

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	Macro	Micro	Macro	Micro	Macro	Micro	Macro	Micro	Macro
4	2	1	3	1	4	1	4	4	4

4.1.4.1.2 Availability of inventory data for different regions

P-LCA: Essential compliance on micro, medium compliance on macro level.

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.

EIO-LCA: Low compliance on micro and medium compliance on macro level.

Region-specific data are available and regional models are appearing [91], but less available than for P-LCA. The availability of EIO-LCA data cannot be influenced by the LCA practitioner since data are provided mostly by government or other sources.

MFA: Compliance in essential parts on both micro and macro level.

The availability of MFA data is comparable to the EIO-data availability but since MFA practitioners are not entirely dependent on other sources the compliance of the method is rated higher.

EMC: Compliance in essential parts on both micro and macro level.

The reasoning for this sub-criterion is the same as for MFA.

Hybrid-LCA: Essential compliance on both micro and macro level.

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 29: **Quantitative evaluation for sub-criterion "availability of inventory for different regions"**

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
3	2	1	2	3	3	3	3	3	3

4.1.4.1.3 Availability of inventory data for all relevant impact categories

P-LCA: Complete compliance on both micro and macro level.

There is no limitation in the method concerning the availability of inventory data for the impact categories.

EIO-LCA: Medium compliance on both micro and macro level.

The currently available inventory data is not entirely suitable for a comprehensive impact assessment including all relevant impact categories.

MFA: Compliance in essential parts on both micro and macro level.

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.

EMC: Complete compliance on both micro and macro level.

There is no limitation in the method concerning the availability of inventory data for the impact categories.

Hybrid-LCA: Essential compliance on both micro and macro level.

The combination of the two basic LCA approaches potentially provides a very good basis for data availability, but the lack of inventory data in EIO-LCA hampers the reality of best impact assessment when EIO-LCA is used to a significant extent.

Table 30:   Quantitative evaluation for sub-criterion "availability of inventory for all relevant impact categories"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	Macro	Micro	Macro	Micro	Macro	Micro	Macro	Micro	Macro
4	4	2	2	3	3	4	4	3	3

4.1.4.1.4 Publicly accessible inventory databases at affordable cost

P-LCA: Medium compliance on micro level, complete compliance on macro level.

On the macro level databases are available and publicly accessible in different varieties, e.g., ecoinvent [97], the European ELCD [94] and the German databases ProBas [93] and Gemis [98]. On the micro level accessibility is more restricted since company-specific data are usually less likely to be publicly accessible.

EIO-LCA: Medium compliance on micro level, complete compliance on macro level.

EIO-LCA is publicly accessible and free, but accessibility on the micro level is comparable to P-LCA.

MFA: Medium compliance on micro level, complete compliance on macro level.

Material flow accounts that are used for MFA are publicly accessible. The focus of the data on the macro level results in the lower score on micro level.

EMC: Medium compliance on micro level, complete compliance on macro level.

Material flow accounts that are used for EMC are publicly accessible. The focus of the data on the macro level results in the lower score on micro level.

Hybrid-LCA: Medium compliance on micro level and complete compliance on macro level.

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

Table 31:   **Quantitative evaluation for sub-criterion "publicly accessible inventory databases at affordable cost"**

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
2	4	2	4	2	4	2	4	2	4

4.1.4.2   Data quality

4.1.4.2.1 Data characteristics

P-LCA: Complete compliance on micro level, low compliance on macro level.

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, but not with macro level applications.

EIO-LCA: Low compliance on micro level, medium compliance on macro level.

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 macro level but only as a first estimate or average on micro level.

MFA: Medium compliance on micro level, complete compliance on macro level.

Environmental and economic information are independent. MFA data is more suitable and consistent on the macro level.

EMC: Medium compliance on micro and macro level.

On micro level, the reasoning for this sub-criterion is the same as for MFA. On macro level, the use of P-LCA data sets involves limitations in the consistency of the information.

Hybrid-LCA: Compliance in essential parts on both micro and macro level.

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 may lead to results where economic and environmental data are not completely independent

Table 32:   Quantitative evaluation for sub-criterion "data characteristics"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	Macro	Micro	Macro	Micro	Macro	Micro	Macro	Micro	Macro
4	1	1	2	2	4	2	2	3	3

4.1.4.2.2 Independent review

P-LCA: Complete compliance on both micro and macro level.

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.

EIO-LCA: Complete compliance on both micro and macro level.

As in all LCA models, internal data review is an essential part of the methodology, and third-party independent data review is part of the LCA studies' peer review process. Cross checks of the underlying economic data are commonly applied.

MFA: No compliance on micro and medium compliance on macro level.

On the macro level, reviews as part of the EUROSTAT guide are taken into account. [40]

EMC: No compliance on both micro and macro level.

The reasoning is the same as for MFA.

Hybrid-LCA: Complete compliance on both micro and macro level.

Reviews are conducted as per the practices of the participating methods.

Table 33:   Quantitative evaluation for sub-criterion "independent review"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	Macro	Micro	Macro	Micro	Macro	Micro	Macro	Micro	Macro
4	4	4	4	0	2	0	2	4	4

4.1.4.2.3 Data representativeness

P-LCA: Complete compliance on micro level, essential compliance on macro level.

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 some restrictions apply due to dependency on statistical data.

EIO-LCA: Low compliance on micro and essential compliance on macro level.

Due to the definition of the method, EIO-LCA can only achieve representativeness for fixed and relatively long time spans. Data sources and types of measurement are fixed, but EIO-LCA has thus far relied mostly on government-mandated and government-sponsored data bases which yield representative results on macro scale, but not necessarily on micro scale. The technology coverage is an average over the whole sector and unable to model technology differences within a micro-scale analysis.

MFA: Medium compliance on both macro and micro level.

For MFA many restrictions mentioned before for EIO-LCA apply as well. Because there is more flexibility in the used data sources, a better representativeness can be achieved in specific applications.

EMC: Medium compliance on micro level, essential compliance on macro level.

The reasoning for this sub-criterion is the same as for MFA on the micro level. On the macro level the combination with LCA based impact assessment leads to a higher scoring.

Hybrid-LCA: Compliance in essential parts on both micro and macro level.

For the hybrid methodology, the scoring gets better compared to EIO-LCA as the use of P-LCA allows achieving higher data representativeness for various applications. However, as long as there is significant use of EIO-LCA based data some restrictions apply resulting in a slightly lower score for the method on the micro level.

Table 34:   Quantitative evaluation for sub-criterion "data representativeness"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
4	3	1	3	2	2	2	3	3	3

4.1.4.2.4 Data documentation

P-LCA: Complete compliance on the micro level, compliance in essential parts on the macro level.

Data are required to be documented in a transparent way, both by the methodology and providers of databases. The only limitation is the adaptation necessary for a macro level use, therefore the compliance is not rated complete.

EIO-LCA: Medium compliance on micro and essential compliance on macro level.

Data documentation is in general available for data characteristics but less so for representativeness aspects and review procedures. The adaptation necessary for a micro level use, which typically is not documented very well, limits the transparency on the micro level.

MFA: Essential compliance on both micro and macro level.

Data documentation is not required, but usually available and ensuring transparency for the data characteristics and representativeness aspects, though not for review procedures.

EMC: Essential compliance on both micro and macro level.

This sub-criterion is the same as for MFA.

Hybrid-LCA: Essential compliance on both micro and macro level.

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 [98].

Table 35:   Quantitative evaluation for sub-criterion "data documentation"

P-LCA		EIO-LCA		MFA		EMC		Hybrid-LCA	
Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
4	3	2	3	3	3	3	3	3	3

4.2   Evaluation of future potential

This chapter highlights those criteria which expected development over the next ten years might have an impact of the applicability of the life cycle methods in the different scope situations. The challenge in evaluating potential changes in the applicability and suitability of the life cycle methods is to display possible development which is realistic and transparent. A conservative scenario was chosen here which is entirely based on development that is already predictable today. For each of the life cycle methods, current or scheduled projects working on issues related to the covered criteria were surveyed and those of the projects selected which can be expected to have significant impact. Results that are already achieved are taken into account as well as objectives that still need to be completed. In the following chapter the selected projects or initiatives are assorted with regard to the sub-criteria of the evaluation scheme which they will influence. On some criteria the

considered projects may have an influence without changing the score, due to an already complete score either on the level of the sub-criteria or on the level of the aspects taken into account for each sub-criterion. In case of the latter a sub-criterion may be improved in respect to one or more aspects, but still lacking a desirable performance for other aspects. The sub-criteria concerned by the regarded projects are mentioned below.

The quantitative results for the evaluation are shown for each sub-criterion in the respective paragraphs. Indicated is the new score and the difference (∆) in comparison with the evaluation of the present situation. An overview of the results can be found in Annex 2 and Table 55.

4.2.1   Projects considered for the future potential

The project "Coordination Action for innovation in Life Cycle Analysis for Sustainability" *(CALCAS)* [98] aims to develop P-LCA by:

- deepening the present models and tools to improve their applicability in difficult contexts while increasing their reliability and usability;

- broadening the LCA scope by better incorporating sustainability aspects and linking to neighbouring models to improve their significance;

- leaping forward the method by a revision/enrichment of foundations, through the crossing with other disciplines for sustainable evaluation.

The improvement of existing models will include areas such as system boundaries, allocation methods and dynamics.

The results of the project are expected to influence the following sub-criteria:

- Detailed expert documentation

- Applicability for broad range of goods and services as well as for broad range of tasks

- Method application by green and consumer NGOs, industry and policy makers

- Plausibility of results

- Method definition for system boundary and multifunctional situations

- Future scenarios

The project *EXIOPOL* [30] is focussed on improving the possibility of application of EIO-LCA within the European Union. It aims to develop further estimates of the external costs of key environmental impacts for Europe and improve the environmentally extended (EE) Input-Output (I-O) framework in the EU, thereby

allowing the estimation of environmental impacts and external costs of different economic sector activities, final consumption activities and resource consumption. The project is expected to influence the following sub-criteria:

- Method application by policy makers

- Clarity of method

- Established communication

- Plausibility of results

- Suitability of the method for comprehensive environmental assessment

- Availability of inventory data for different regions

The **UNEP/SETAC Life Cycle Initiative** [13] 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. It is expected to contribute to the following sub-criteria:

- Comprehensible calculation and transparency

- Applicability for broad range of goods and services

- Method application by green and consumer NGOs, industry and policy makers

- Clarity of method

- Established communication

- Existence of scientific societies

- Plausibility of results

- Method definition for system boundary

- Suitability of the method for comprehensive environmental assessment

- Number of available tools

- Availability of inventory data for different regions

Currently **national LCA databases** are being developed (further) by several countries, including the USA, Sweden, Malaysia, Canada and Korea. 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, too. They therefore influence the following sub-criteria:

- Comprehensible calculation and transparency

- Broad range of goods and services

- Broad range of tasks

- Method application by policy makers

- Time series

- Availability of inventory data for different regions

- Publicly accessible inventory databases at affordable cost

- Data documentation

A significant improvement of consistency and quality across P-LCA data, methodological issues, and studies is expected in the next few years by the implementation of the ***International Reference Life Cycle Data System (ILCD)***, which is coordinated in Europe by the JRC IES through the EU Platform on LCA [11]. The project will influence the following sub-criteria:

- Availability of guidelines or code of conduct

- Broad range of goods and services

- Method application by green and consumer NGOs as well as by industry and policy makers

- Reproducibility

- Established communication

- Definition of system boundary

- Time series

- Availability of inventory data for the whole life cycle

- Publicly accessible inventory databases at affordable cost

- Data representativeness

- Data documentation

EUROSTAT has recently tendered a series of six projects which aim at establishing an environmentally-extended multi-regional input-output system for Europe, see [see 99]. 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. The projects are expected to influence the following criteria:

- Method application by policy

- Availability of inventory data for different regions

- Availability of inventory data for all relevant impact categories

- Data representativeness

The **Stocks and Flows Project (STAF)** conducted by Yale University evaluates stocks and flows of significant materials throughout the world for different time spans [100]. 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.

The STAF project is expected to have an impact on the following sub-criteria:

- Time series

- Future scenarios

- Availability of inventory data for different regions

- Publicly accessible inventory databases at affordable cost

- Data representativeness

The level of research on and application of MFA differs largely for different regions of the world. Japan is one of the countries where MFA is well established and therefore **two Japanese initiatives concerning MFA** are taken exemplarily into account here. The Ministry of Environment (MoE) aims to disclose information through Environmental and Sustainability Reporting by the industry and has published guidelines for the accounting of MFA relevant data. The Ministry of Economy, Trade and Industry (METI) is concerned with material efficiency and aims to improve implementation and use of environmental indicators, also through the provision of guidelines and the information of stakeholders (see [101]). Though these initiatives are by default focussed on the Japanese situation they can be expected to influence several of the criteria in this evaluation, exemplarily but also as forerunner for other regions. Affected sub-criteria are:

- Availability of guidelines or code of conduct

- Method application by industry

- Time series

- Availability of inventory data for different regions

OECD council recommendation on resource productivity which was adopted in 2008 is likely to have an impact on EW-MFA applications as member countries are encouraged by it to improve their analysis of material flows and related environmental impacts. The recommendation will also very likely influence MFA practice in non-member states as cooperation with non-member countries is recommended [102].

Research which will have an impact on the EMC has been tendered by EUROSTAT [103], but as there are no results of this work yet, there is no basis for a 10-year evaluation of EMC and the method has been excluded form this part of the study.

4.2.2   General criteria

4.2.2.1   Method documentation and transparency

4.2.2.1.1 Availability of guidelines or code of conduct

The evaluation of the sub-criterion is expected to change due to the work of the Japanese initiatives on MFA (see [101]), especially on industry level since they are both concerned with the dissemination of information on the micro level through the publication of guidelines and a handbook. Therefore an increase of the micro level evaluation of MFA compliance is assumed, though only a marginal one since the improvement can be noted with any certainty for Japan only.

The ILCD will provide various new guidance documents for P-LCA. However, as at the moment commitments to apply these guidelines cannot be presumed, the score has not been changed.

Table 36: Quantitative evaluation for sub-criterion "availability for guidelines or code of conduct" for the future potential

	P-LCA		EIO-LCA		MFA		Hybrid-LCA	
	Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
Score	3	3	2	3	1	3	2	2
Δ	0	0	0	0	+1	0	0	0

4.2.2.1.2 Comprehensible calculation and transparency

The sub-criterion is influenced by the work of the Life Cycle Initiative as well as the development of national databases. With their extensive work on collecting and providing data on previous LCA applications they improve the documentation of calculation. The method where this can be expected to have the most pronounced effect is the hybrid approach of LCA where calculation at the moment is less

transparent. The influence on the other methods is not expected to be large enough to justify a change in the scoring.

Table 37: **Quantitative evaluation for sub-criterion "comprehensible calculation and transparency" for the future potential**

	P-LCA		EIO-LCA		MFA		Hybrid-LCA	
	Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
Score	4	2	3	4	2	4	2	2
Δ	0	0	0	0	0	0	+1	+1

4.2.2.2   Applicability

Similarly, as for the previous criterion the work of the Life Cycle Initiative and the national databases will influence the sub-criteria for applicability "broad range of goods and services" and "broad range of tasks". The applicability of the life cycle methods to different stages of the value chain is expected to improve as best practice guidelines for different applications evolve and information from different sources and therefore different levels is combined and provided. Since the extent of this is not discernible from the information currently available these improvements are not realised in a changed quantitative scoring.

4.2.2.3   Stakeholder acceptance

4.2.2.3.1 Method application by green and consumer NGOs

Though presently there are no applications of any of the life cycle methods by NGOs, expected facilitated data accessibility might change this, though the potential is evaluated tentative due to the current lack on application. The information, data and guidelines provided by ILCD are expected to facilitate application and thereby add to acceptance and application by NGOs. CALCAS [98] and the Life Cycle Initiative also work on capacity building: improved information and incorporation in tools facilitating the method for different stakeholders. With heightened NGO awareness the application of the LCA approaches can be expected at least on their primary application level, i.e. on macro level for EIO-LCA and on micro level for P-LCA. Hybrid LCA is excluded here since so far they have hardly been applied at all and their application needs to become more regular in general before NGO application can be assumed.

Table 38: Quantitative evaluation for sub-criterion "method application by green and consumer NGOs" for future potential

	P-LCA		EIO-LCA		MFA		Hybrid-LCA	
	Micro	Macro	Micro	Macro	Micro	Macro	Micro	Macro
Score	1	0	0	1	0	0	0	0
Δ	+1	0	0	+1	0	0	0	0

4.2.2.3.2 Method application by industry

With simplified access to reliable databases and more straightforward information on best practice regarding models or methods as provided by the ILCD, industry application will be facilitated. Especially on the macro level, where greater improvement potential exists, greater industry application is expected for P-LCA due to the ILCD's information provision. The Life Cycle Initiative with their dissemination of successful applications and work on business benchmarking will influence the level of usage by individual companies and on sector level. Acceptance and applicability can also be improved by the Life Cycle Initiative through its capacity building modules for SMEs. However, an improved industry application is not expected for P-LCA: on the micro level it is already evaluated complete today, macro level applications by industry are scarce at best and if desired more likely to be accomplished by EIO-LCA or a hybrid approach.

Due to the provision of guidelines by the Japanese initiatives on MFA as mentioned above an improved acceptance and resulting application of MFA by industry is expected which leads to a higher compliance of MFA on the micro level.

Table 39:   Quantitative evaluation for sub-criterion "method application by industry" for future potential

	P-LCA		EIO-LCA		MFA		Hybrid-LCA	
	Micro	Macro	Micro	Macro	Micro	Macro	Micro	Macro
Score	4	2	2	2	2	3	2	1
Δ	0	+1	+1	+1	+1	0	+1	+1

4.2.2.3.3 Method application by policy makers

Similar to the previous sub-criterion change will occur for the political application due to the Life Cycle Initiative and information provided by the ILCD. In addition an influence by all other assessed projects can be expected as well since they are usually initiated on a political level. Changes for the quantitative evaluation are predictable for EIO-LCA, MFA and Hybrid LCA (scoring of P-LCA is complete already

for the present day evaluation). For EIO-LCA and MFA at least some application on the micro level is assumed in the future (for the macro level compliance is assumed for the present day evaluation already), for Hybrid LCA the potential is higher due to the combination of EIO- and P-LCA. Hybrid LCA is fairly new but is expected to move on from a purely scientific level to real life application.

Table 40: Quantitative evaluation for sub-criterion "method application by policy makers" for future potential

	P-LCA		EIO-LCA		MFA		Hybrid-LCA	
	Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
Score	4	4	1	4	1	4	2	2
Δ	0	0	+1	0	+1	0	+2	+2

4.2.2.4   Communicability

4.2.2.4.1 Clarity of methods

The Life Cycle Initiative aims to make the steps between clearer and relations more transparent. Especially EIO-LCA and Hybrid LCA will profit here, though on the whole the evaluation changes only slightly.

Table 41: Quantitative evaluation for sub-criterion "clarity of method" for future potential

	P-LCA		EIO-LCA		MFA		Hybrid-LCA	
	Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
Score	3	2	2	3	2	4	2	2
Δ	0	0	+1	0	0	0	+1	+1

4.2.2.4.2 Established communication

More potential is predictable for the existence of established communication since it will rise with increasing application (see above), the change can mainly be attributed to the Life Cycle Initiative as well as the ILCD due to their aim to provide best-practice guidelines and strategies for communication.

Table 42: **Quantitative evaluation for sub-criterion "established communication"**

	P-LCA		EIO-LCA		MFA		Hybrid-LCA	
	Micro	Macro	Micro	Macro	Micro	Macro	Micro	Macro
Score	4	3	2	3	1	3	2	2
Δ	0	+1	+1	+1	0	0	+1	+1

4.2.3 Methodological criteria

4.2.3.1.1 Plausibility of results

EXIOPOL [30] aims to improve the data on environmental impact caused by economic activities and therefore to enhance the correlation between used data and environmental assessment which results in an improved plausibility of EIO-LCA. For the other considered life cycle methods no changes are discernible

Table 43: Quantitative evaluation for sub-criterion "plausibility of results" for future potential

	P-LCA		EIO-LCA		MFA		Hybrid-LCA	
	Micro	Macro	Micro	Macro	Micro	Macro	Micro	Macro
Score	4	2	2	3	2	3	3	3
Δ	0	0	+1	+1	0	0	0	0

4.2.3.2 Methodological completeness

4.2.3.2.1 Method is defined for system boundary

The Calcas project [98] strives specifically to improve the clarity of boundary setting when applying P-LCA while the work of the ILCD Handbook and Life Cycle Initiative will do so with the provision of manuals for application on a more general LCA level. Hybrid LCA is therefore expected to be improved alongside P-LCA (the EIO-LCA boundaries are already clearly set today).

Table 44: Quantitative evaluation for sub-criterion "Method is defined for: system boundary" for future potential

	P-LCA		EIO-LCA		MFA		Hybrid-LCA	
	Micro	Macro	Micro	Macro	Micro	Macro	Micro	Macro
Score	3	1	2	3	1	4	3	3
Δ	+1	0	0	0	0	0	+1	0

4.2.3.2.2 Method is suitable for comprehensive environmental assessment

In addition of its impact on the plausibility of EIO-LCA, the outcome of Exiopol may well improve the suitability for environmental assessment carried out by EIO-LCA. It aims at procedures for impact assessment as well as improving the method's general appropriateness for impact assessment which results in a higher score of EIO-LCA on the macro level (Exiopol is dealing with macro level application). Though for instance the Life Cycle Initiative is also concerned with improvements in impact assessment which might affect P-LCA as well, there is no work visible which would overcome the basic lack that coverage of the entire impact situation is ensured.

Table 45:   Quantitative evaluation for sub-criterion "Comprehensive environmental assessment" for future assessment

	P-LCA		EIO-LCA		MFA		Hybrid-LCA	
	Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
Score	3	3	2	3	0	0	3	3
Δ	0	0	0	+1	0	0	0	0

4.2.4   Technical criteria

4.2.4.1   Availability of software tools

4.2.4.1.1 Number of available tools

The objective of the Life Cycle Initiative to provide tools for different applications, namely including regional issues and simplified tools will have a significant impact on this sub-criterion. So far Hybrid LCA is hardly included in conventional LCA software but with increasing application of the method this can be expected to change, for micro as well as macro level studies. For P-LCA this development will be more pronounced on the macro level since tool availability is very satisfactory on the micro level already. For the same reason no change is expected for EIO-LCA.

Table 46:   Quantitative evaluation for sub-criterion "number of available software tools" for future potential

	P-LCA		EIO-LCA		MFA		Hybrid-LCA	
	Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
Score	3	3	3	4	4	4	3	3
Δ	0	+1	0	0	0	0	+1	+1

4.2.4.2 Suitability for time specific models

4.2.4.2.1 Time series

The STAF project as well as the initiatives of the Japanese ministries will influence the compliance of MFA in this sub-criterion since they lead to a more regular and continuous data collection and provision both on the macro and the micro level.

Table 47: Quantitative evaluation for sub-criterion "time series" for future potential

	P-LCA		EIO-LCA		MFA		Hybrid-LCA	
	Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
Score	3	2	3	3	3	3	2	2
Δ	0	0	0	0	+1	+1	0	0

4.2.4.2.2 Future scenarios

The deduction of future development is an explicit application field of the STAF project and will therefore improve the suitability of MFA for this sub-criterion on the macro level (the STAF models are region oriented; therefore no micro level improvement is expected here).

Table 48:   Quantitative evaluation for sub-criterion "future scenarios" for future potential

	P-LCA		EIO-LCA		MFA		Hybrid-LCA	
	Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
Score	3	2	1	1	1	2	2	2
Δ	0	0	0	0	0	+1	0	0

4.2.5   Data criteria

The greatest changes and improvement potential are expected for data provision, regarding the background as well as quality as well as differentiation.

4.2.5.1   Data availability and accessibility

4.2.5.1.1 Availability of inventory data for different regions

All, the growing national databases as well as the ILCD Data Network promoted by the European Platform on LCA, the Life Cycle Initiative and the work undertaken by EUROSTAT are concerned with improving data availability. Since their work is not only focussed on better data provision in general but also honours the fact that region specific applications of life cycle methods have a growing demand, these projects will

greatly contribute to region specific - both geographic and technologic - data. However, no complete data availability is assumed for any of the considered methods since a worldwide region specific data provision cannot be expected within the next 10 years considering the amount of countries and regions which are not in the process of establishing individual databases yet.

The projects focused on the development of MFA will have an impact on the availability of regional data but the evidence of their work does not suggest a complete compliance within the next 10 years. Firstly, work is focused on specific substances, not necessarily on comprehensive data provision; secondly, uneven distribution of improvements over the world does not justify a complete scoring.

Table 49: Quantitative evaluation for sub-criterion "availability of inventory data for different regions" for future potential

	P-LCA		EIO-LCA		MFA		Hybrid-LCA	
	Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
Score	3	3	2	3	3	3	3	3
Δ	0	+1	+1	+1	0	0	0	0

4.2.5.1.2 Availability of inventory data for all relevant impact categories

With regard to EIO-LCA the work undertaken by EUROSTAT will improve the data situation for the environmental assessment, the score is therefore increased.

Table 50: Quantitative evaluation for sub-criterion "availability of inventory for all relevant impact categories"

	P-LCA		EIO-LCA		MFA		Hybrid-LCA	
	Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
Score	4	4	3	3	3	3	3	3
Δ	0	0	+1	+1	0	0	0	0

4.2.5.1.3 Publicly accessible inventory databases at affordable cost

The availability and accessibility of public inventory databases will be influenced mainly by the nationally and supranationally emerging databases, though maybe not all of them will be free of charge but their accessibility at affordable cost is deemed higher than for the currently prevailing private databases. These databases will have impact on all the methods. For MFA and EIO-LCA however, no change in the quantitative evaluation is determined since no change on the micro level is identifiable for these methods and they show complete compliance with the sub-

criterion already today. For P-LCA and Hybrid LCA on the other hand improvement changing the scoring on the micro level can be expected.

The STAF project will improve the availability of databases for MFA on a macro level further, but since the compliance is already evaluated as complete today there is no change in scoring.

Table 51: Quantitative evaluation for sub-criterion "publicly accessible inventory databases at affordable cost" for future potential

	P-LCA		EIO-LCA		MFA		Hybrid-LCA	
	Micro	Macro	Micro	Macro	Micro	Macro	Micro	Macro
Score	3	4	2	4	2	4	3	4
Δ	+1	0	0	0	0	0	+1	0

4.2.5.2   Data quality

4.2.5.2.1 Data representativeness

The ILCD Data Network is expected to influence data representativeness but as P-LCA compliance with this sub-criterion is already complete/ essential on micro resp. macro level the quantitative evaluation does not differ.

The projects initiated by EUROSTAT will improve data representativeness for EIO-LCA on the macro level for at least the EU-27 significantly. Compliance is therefore increased to 4.

The STAF project is expected to improve the data representativeness of MFA data in terms of source and technology coverage due to its broad approach and inclusion of all different world regions. This improvement is limited; however, to the macro level since the system boundary of the research activities is regional.

Table 52: Quantitative evaluation for sub-criterion "data representativeness" for future potential

	P-LCA		EIO-LCA		MFA		Hybrid-LCA	
	Micro	Macro	Micro	Macro	Micro	Macro	Micro	Macro
Score	4	3	1	4	2	3	3	3
Δ	0	0	0	+1	0	+1	0	0

4.2.5.2.2 Data documentation

Lastly, the documentation of available data will be improved by increasing its transparency as part of the outcome of national databases. Though there is no

commitment to universal quality standards by the national projects and the ILCD, most of them have introduced differentiated procedures to ensure quality by applying reviews or at least documenting the level of quality in a transparent way. Therefore data documentation is improved for EIO-LCA on the macro level (the identified issues on the micro level are not touched by this) and for Hybrid LCA on both the micro and macro level. The quantitative scoring for P-LCA is not changed since the limitations on the macro level remain and its compliance is already complete on the micro level.

Table 53: **Quantitative evaluation for sub-criterion "data documentation"**

	P-LCA		EIO-LCA		MFA		Hybrid-LCA	
	Micro	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**	**Micro**	**Macro**
Score	4	3	2	4	3	3	4	4
Δ	0	0	0	+1	0	0	+1	+1

5   Discussion of the Life Cycle Methods

This chapter summarises the outcomes for each individual method, i.e. their accordance with the overall suitability for the questions under study. The detailed comprehensive results are shown both for the level of criteria and sub-criteria in Annex 2.

5.1   P-LCA

Micro level

On the micro level the process-based LCA is the most developed, with complete compliance in many sub-criteria.

Limitations are found – highlighted by medium compliance for the sub-criteria – on system boundary definition and on public accessibility of inventory data bases, the former being an intrinsic weakness of the methodology, the latter open for improvement.

Under the conditions relevant for this study, the main strength points of P-LCA are the acceptance by stakeholders, the scientific soundness and the data quality.

Macro level

The overall suitability of the method is lower, in comparison to its micro level. In general the documentation and transparency have weak points, system boundaries are less well defined, the application level by industry is lower and data characteristics are of lower quality. In addition, the scientific soundness scores equally lower than on micro level. As in the previous case, stakeholder acceptance is still fairly high, while data quality and scientific soundness show room for improvements

Future potential

For the evaluation of future potential, three of the sub-criteria were found to be likely to change on both micro level ("Method application by green and consumer NGOs", Method is defined for system boundary" and "Publicly accessible inventory databases at affordable cost") and macro level ("Established communication", "Number of available software tools", "Availability of inventory data for different regions"). In combination these issues led to only a slight 10-year improvement potential for the P-LCA under the given assumptions. However, there are aspects related to P-LCA which are expected to improve over the next years, especially due to the efforts visible on data availability, but since they were already given the full

score or concern simply just one sub-criterion out of the many considered this improvement is not revealed here.

5.2   EIO-LCA

Micro level

EIO-LCA shows its very good performance with regard to reproducibility, documentation and the diverse results on the micro level. While its calculation is comprehensible, its reproducibility is good and the availability of tools applicable to the method on an appropriate level, the suitability of EIO-LCA for comprehensive environmental assessment and data availability are overall only medium. A great limitation is also shown by the low scoring for plausibility and stakeholder acceptance. With regard to clarity of method and suitability for time related questions there is a great potential for improvement as well.

Macro level

For the macro level EIO-LCA reveals a much higher applicability. Improved performance in comparison to the micro level is especially obvious in the method description, stakeholder acceptance and the communicability of the method as well as its suitability for time specific models (due to the possibility of time models) and data availability as the method scores especially high for these criteria. Other criteria which show rather poor compliance on the micro level improve greatly: this concerns especially communicability, but also - to a lesser extent - data issues, acceptance by stakeholder and suitability for time related issues.

Future potential

For the future evaluation EIO-LCA shows likely improvement for a variety of sub-criteria. On the micro level most notably is the improved performance in the sub-criterion plausibility of results. Performance was also improved for stakeholder acceptance, communicability and partly data availability. Even more than on the micro level the improvement potential becomes clear for the macro level. In addition to the criteria mentioned for the micro level, there is also methodological improvement on the issue of environmental impact assessment and better data quality to be expected.

5.3   MFA

Micro level

The results for MFA widely differ; the method reveals complete or no compliance with several criteria. It should be kept in mind, however, that while MFA does not include an environmental assessment, it can well deliver the basis for one. On the micro level MFA shows good compliance for objectivity issues as well as the availability of software but apart from these its compliance is rather low. This holds especially true for stakeholder acceptance but also method documentation and transparency.

Macro level

On the macro level the results for MFA improve greatly. In contrast to the micro level MFA shows on the macro level a much improved documentation and transparency. The stakeholder acceptance and data availability increase significantly, too. Apart from the availability of software the communicability of the method is excellent on the macro level as well. In comparison to the micro level, MFA especially shows better suitability with regard to method documentation and transparency as well as stakeholder acceptance

Future potential

For the future evaluation a potential improvement can be deduced for MFA, both on micro and on macro level. Even though the method is likely to show a better suitability for the micro level over time than it does now and will also increase for documentation and stakeholder acceptance (most influential for the micro level), the overall picture does not change significantly: MFA still lacks greatly in its suitability for micro level issues. On the macro level on the other hand MFA is able to improve more clearly. It is noteworthy that MFA is the only method which at the moment seems likely to improve in the time related criteria, for in the macro level evaluation MFA not only improves in its suitability for time series but also for its suitability for future scenarios. With improved availability of data the knowledge about the predominant emission sources of specific substances increases, which can be used to investigate how to manage the environmental impact for these substances.

5.4   EMC

Micro level

EMC achieves medium or higher compliance in several criteria on the micro level. On the other hand the method reveals major deficiencies in both documentation and praxis related criteria which apart from the macro level focus of the method can be attributed to its recent development.

Macro level

As with the two previous methods the results are higher on the macro level, though for different reasons. The improvement is not mainly caused by a few specific criteria but rather due to an overall improvement, based on its macro level focus. EMC achieves the best result of all five evaluated methods for methodological completeness on the macro level.

Future potential

As explained in 4.2 the future development was not assessed here due to the lack of evident projects improving it.

5.5   Hybrid LCA

As already indicated by the evaluation of the single criteria, Hybrid LCA is often able to incorporate the specifics of either P-LCA or EIO-LCA, whichever is more advantageous. This leads to a medium suitability of Hybrid LCA on the micro level and a performance on the macro level which is comparable to both basic LCA methods. Even though the overall performance is high, the deficiencies of the approach are revealed in praxis related criteria.

Micro level

On the micro level its strengths lay especially in applicability and in the data criteria. The weaknesses on the other hand can be found in stakeholder acceptance and communicability of the method.

Macro level

On the macro level the applicability is as high as on the micro level, the good results for the data criteria are even more pronounced. Apart from that the results are similar on both application levels due to combination of P-LCA and EIO-LCA.

Future potential

The greatest potential for improvement within the next 10 years is found for Hybrid LCA; both on micro and macro level. The transparency of the calculation is expected to improve with its enhanced documentation by the national databases, thus leading to a medium compliance. The stakeholder acceptance of the method is expected to increase which is in line with the increased application by different stakeholder groups. In accordance with the improved results of EIO-LCA, Hybrid LCA also showed increased compliance in communicability and data documentation on micro and macro level. In accordance with expected development for P-LCA, issues of boundary setting will be solved for Hybrid LCA as well as accessibility of public databases on the micro level. Also for both levels the number of available software tools is expected to increase once the method is actually applied in real life decision making.

6   Final Comparison of the Life Cycle Methods

6.1   Micro level applications

For the application on a micro level under present circumstances the result of the study at hand is unambiguous: process-based LCA achieves a significantly higher overall score than any of the other life cycle methods. An overview of the quantitative results (present evaluation) for each method in the general criteria is given in Figure 6, an overview of the results in the specific criteria (including data, methodological and technical issues) in Figure 7.

With some limitations regarding the setting of system boundaries and reproducibility P-LCA is evaluated throughout as well or better than all other considered methods in this scope situation. The most pronounced advantages compared to the other methods can be found in method documentation and transparency, scientific soundness and data quality.
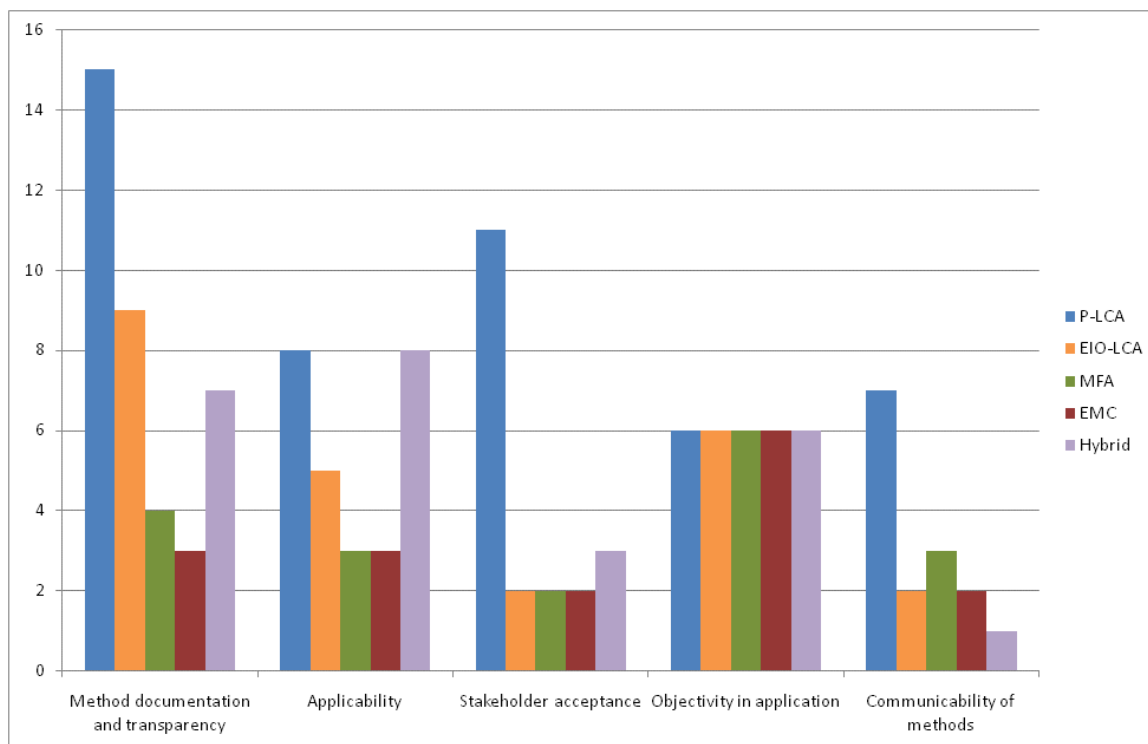
Figure 6: Quantitative results of the methods in the general criteria on the micro level

EIO-LCA, MFA and EMC all show a comparable suitability, reaching about half the quantitative score of P-LCA. While EIO-LCA shows a low to essential compliance with most criteria, the results for MFA and EMC are more widespread since they reveal complete or no compliance with several criteria. Their strengths lie in objectivity and practical considerations such as the availability of software (except EMC for which no software is available), where the performance is similar to that of

P-LCA. However, these strong points are not specific to the scope situation but hold true for the methods in general.

Common weak points of EIO-LCA, MFA and EMC can be found mainly in the issues of stakeholder acceptance and the existence of previous communication experiences since these methods have not been applied to a micro level scope regularly. Furthermore they show deficiencies in the issue of data quality. In comparison to the other methods EMC reveals additional shortcomings in the area of scientific soundness. It is, however, methodologically almost complete, significantly more than EIO-LCA and MFA. Hybrid LCA, as combination of P-LCA and EIO-LCA, consequently arrives in between P-LCA and the other methods. Its strengths lie for one in data availability and data quality, but also in objectivity and broad applicability, its main weaknesses in comparison to P-LCA can be found in criteria relating to previous applications (as there have been none).
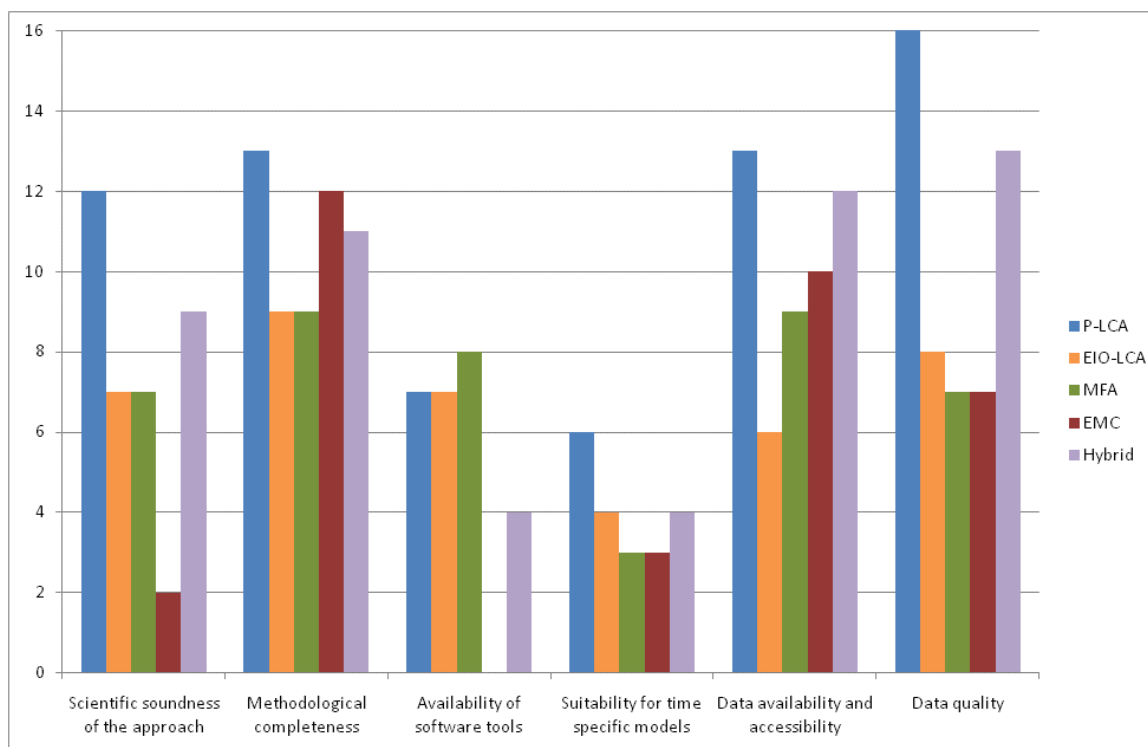
Figure 7: Quantitative results of the methods in the specific criteria on the micro level

For the evaluation of a 10-year time scenario the improvement potential for the P-LCA is limited on the micro level, mainly since its present compliance and suitability for micro level studies is already very high. However, the two issues identified above as weak points in comparison with the other methods are expected to improve. On the other hand Hybrid LCA shows a great potential since some of its assessed weaknesses can be remedied if an increasing application is assumed for the next 10 years. The suitability of EIO-LCA and MFA is assumed to improve as well, though to

a smaller extent, thereby not significantly changing the outcome of the evaluation for the present situation.

6.2 Macro level applications

In comparison with the micro level, the overall suitability of P-LCA is lower; the suitability of the other methods higher for the macro level scope situation; leading to a more evenly distributed result. On the whole there are only minor differences. All three basic methods (P-LCA, EIO-LCA, MFA) are documented very well with EIO-LCA scoring the highest in documentation and transparency, while Hybrid LCA and EMC lack such a comprehensive documentation. The same is true for issues related to previous applications (acceptance, existing examples), as revealed on the micro level. The strengths of Hybrid LCA and EMC lie in data issues since they are likely able to combine different data sources better than the basic approaches. MFA shows the best suitability in stakeholder acceptance and communicability.

An overview of the quantitative results (present evaluation) for each method in the general criteria is given in Figure 8, an overview of the results in the specific criteria (including data, methodological and technical issues) in Figure 9.
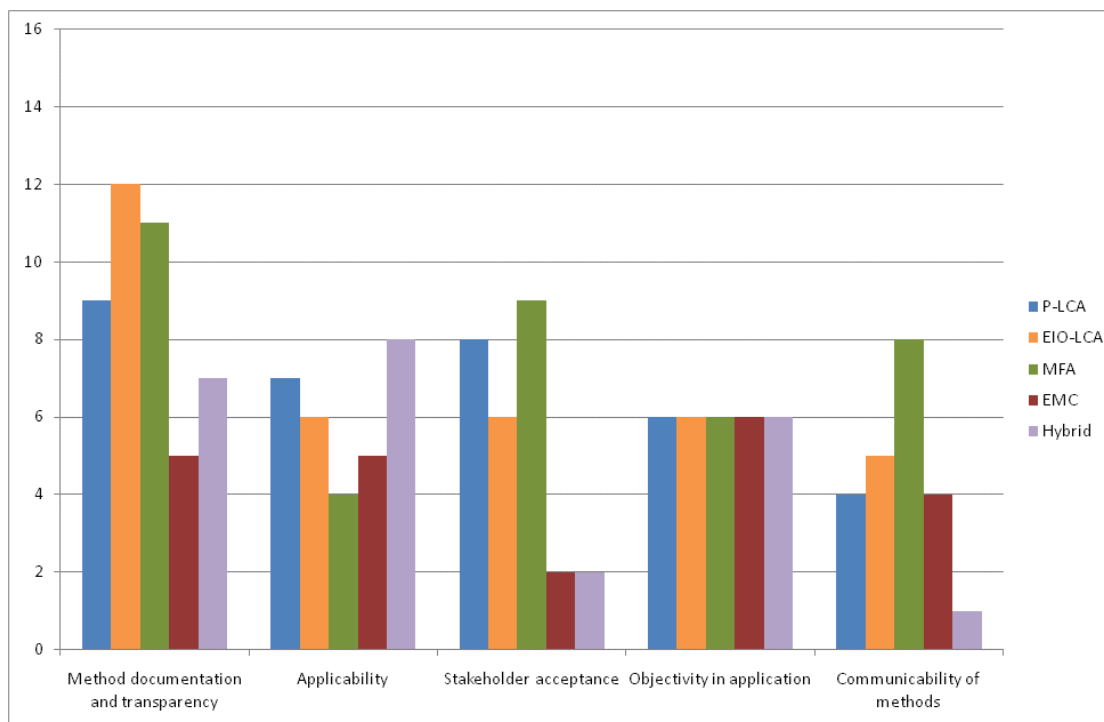
Figure 8: Quantitative results of the methods in the general criteria on the macro level
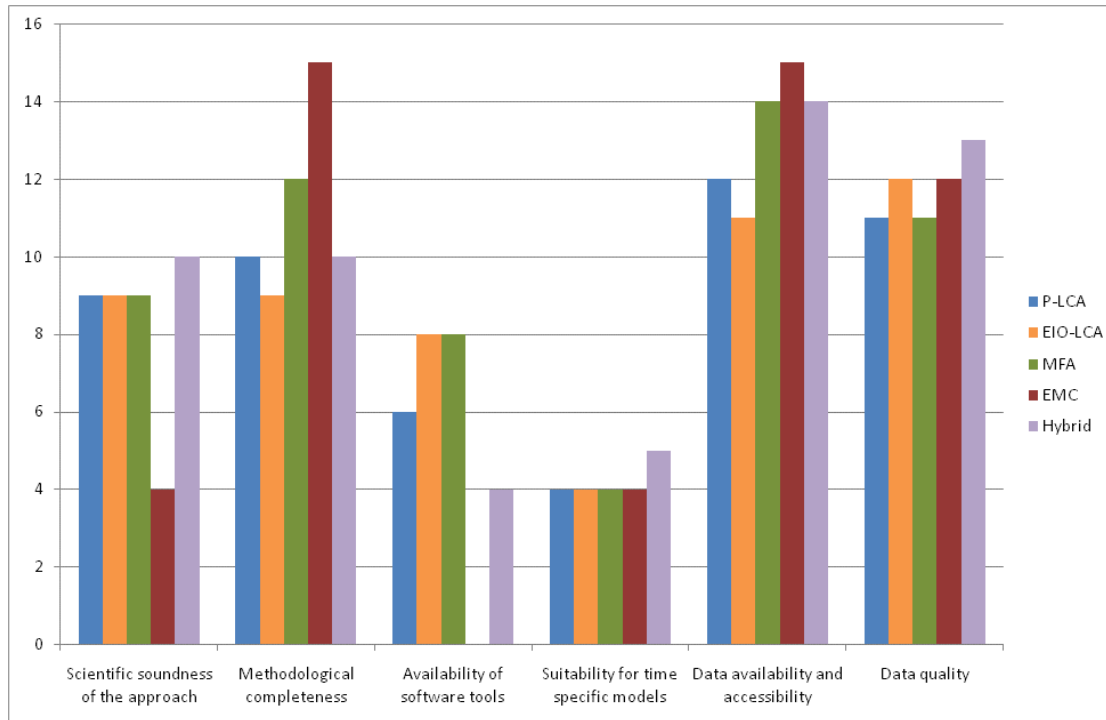
Figure 9: Quantitative results of the methods in the specific criteria on the macro level

The 10-year scenario confirms the overall result of the macro level. As on the micro level the improvement potential of P-LCA is limited, while Hybrid LCA and - to a slightly lesser extent - the EIO-LCA and MFA are expected to amend some of their weaknesses. For Hybrid LCA the issue of comprehensible calculation and transparency is expected to improve. As apparent on the micro level, MFA does not include an environmental assessment, neither now nor in the future. However, MFA creates the basis of knowledge about emission sources which can be used to investigate how to manage the environmental impact.

7   Conclusions and Outlook

The objective of this study was to evaluate the strengths and weaknesses of different life cycle based approaches for assessing environmental impacts. The micro level perspective is typically connected to situations of decision making concerning a specific product, process, technology or site. The macro level perspective is focussed on, for instance, monitoring the impacts of production and consumption at the level of EU or Member States considering sectors.

Regarding micro level applications, Process-based LCA is clearly the strongest method; a result which is not likely to change significantly over the next 10 years. The method is found to be scientifically sound and well documented as well as transparent. It is also significantly more accepted by stakeholders on this level than the other evaluated methods. Though there is improvement potential in data and time related issues, the method is very well defined and equipped with regard to the evaluation criteria taken into account in this project.

For future applications P-LCA will remain most suitable for micro scale applications if development occurs as expected here. The Hybrid Approach (Hybrid LCA), which at the moment does not play a significant role, is likely to become more suitable and more relevant as it is expected to solve the problems in vital issues mentioned above, such as documentation and communicability.

Economic Input-Output LCA (EIO-LCA) on the other hand is not expected to become significantly more relevant for micro level applications than it is at the moment. The method shows a generally low compliance on the micro level with most criteria taken into account for this study and these shortcomings are not likely to be overcome even though some improvements are expected with regard to data availability and communicability.

MFA shows a more diverse picture, as it has low compliance with issues of documentation but is at the same time more easily communicated and shows higher data availability than EIO-LCA.

EMC is found to be suitable in principle for micro level applications, but it must be kept in mind that the method was clearly developed with a macro focus. At the moment the method has not been applied and its future development cannot be assessed with the tentative approach chosen here. A different approach is needed for an estimation of its future potential.

On the macro level, the result is more balanced: All five life cycle methods are evaluated approximately the same.

MFA shows advantages in its communicability and in its acceptance by stakeholders, while EIO-LCA is transparent and best documented. EMC on the other hand, though not of practical importance at the moment reveals a good potential with

regard to issues of methodological completeness and data availability. The Hybrid LCA approaches show a similar compliance with data issues. For the future potential a similarly balanced result is shown for macro applications. All methods are expected to improve some of their weak points, with the greatest improvement potential within 10 years revealed for Hybrid LCA.

MFA takes up a special position within this study, as the method does not include an environmental impact assessment. However, without the consideration of the environmental impact assessment MFA showed very good suitability on the macro level. Approaches to solve the issue should therefore be recommended. The approach taken with the EMC was one effort to do so but different approaches might evolve in the future.

In addition it is emphasised that the evaluation of the five life cycle methods was carried out on a theoretical basis only. Methodological issues have thereby been taken into account along with general practical ones. But especially for the latter, significant differences can not always be revealed on a theoretical basis. To confirm the results it is therefore recommended to conduct a further comparative evaluation on a case study level.

It is equally important to note that the analysis in this project was conducted for methods distinguishing between macro and micro scale applications. Depending on the scope of the application, different methods may be used. In some cases, more than one of the methods analysed may be adopted.

In general, the use of P-LCA, EIO-LCA, and Hybrid-LCA are more likely to be interchangeable in a given application. While P-LCA is more clearly suitable in applications for products and product-groups, micro scale, it will be desirable to consider more than one method at the macro scale due to the differences in strengths and weaknesses across the methods.

MFA and EMC have specific applications and are therefore less interchangeable with the others.

The evaluation of the future potential of the methods was carried out here very cautiously. This means that expected improvements were based on projects developing the methods which are already visible today - and therefore have already begun - and the assumption that these projects will reach their targets. To improve this evaluation, strategic scenario analyses should be applied.

Despite these needs for further research, the undertaken study can contribute to the development of sustainability indicators by providing a scientific basis for the selection of the appropriate life cycle method in a specific decision-making situation.

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Annex 1: Evaluation scheme

Table 54: **Criteria and aspects to be evaluated**

Criteria	Sub-criteria	Aspects to be considered
Method documentation and transparency	Availability of guidelines or code of conduct	• Published and accessible • Are applied • Commitments for application on different scope levels • Widely accepted
	Detailed expert documentation	• Comprehensible • Reviewed and reliable source • Published and accessible • Number of methodological papers as found in scientific online databases
	Comprehensible calculation and transparency	• Accessibility to basic data • Detailed documentation of calculation • Functional model, e.g. dependencies and relations are apparent
	Availability of standardisation for method	Level of standardisation • in preparation • in progress • national standards • international standardisation available

Criteria	Sub-criteria	Aspects to be considered
Applicability	Broad range of goods and services	• Method is applicable for a broad range of goods and services, with as few exceptions as possible: • in all stages of the value chain (consumer goods, intermediate goods, etc.) • goods only or for both, goods and services • Flexibility of method to adjustments in systems definition (depending on goal & scope of study)
	Broad range of tasks	• Possibility of comparison of systems • Improvement analysis • detail in which changes can be analysed • identification and tracing of drivers • identification of cause-effect-chains • Level of improvement (single products/type of product/sector/region) • Deduction of potential changes (including on policy level) • Identification of risks • Marketing/communication applications
Stakeholder acceptance	Inclusion of stakeholders	• Inclusion in development • Inclusion in decision making (based on method application) • Stakeholder groups and their interests are treated equally - no favouritism
	Method application by green and consumer NGOs	• Range of application regarding scope • Range of uses (publication, information of public, legislative proposals, exerting pressure on industry, policy)
	Method application by industry	• Level of usage by companies, by industry sectors • Availability of voluntary commitments to apply method

Criteria	Sub-criteria	Aspects to be considered
	Method application by policy makers	• Level of policy decision • Type of policy • Number of issued policies • Number of countries applying method on policy level
Objectivity in application	Reproducibility	• Results do not depend on user applying the method • Results do not change with repeated application
	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) • Necessary value choices are clearly stated • Possibility of uncertainty analyses and quantification of influence of assumptions
Communicability of methods	Clarity of method	• Simplicity of basic concept, also for non-experts • Relation between steps of method are comprehensible, connections logical and transparent • Unambiguousness of result
	Established communication	• Existence of tools for communication (e.g. EPD) • Previous communication examples exist, which can be consulted for support • Level/goal/success of previous communication examples • Adaptability to cover different target audiences
Scientific soundness of the approach	Scientific societies exist	• Promotion of research/ scientific discussion through societies • Exist on national or international level • Cover differences in regions

Criteria	Sub-criteria	Aspects to be considered
	Validation/ _verfication_ checks	• Checks for sensitivity, consistency, errors, etc. are mandatory • Possibility of disaggregation of results against environmental measurements • Critical and peer (with lesser significance) reviews are mandatory for key parts of method/results
	Plausibility of results	• Direct measurement of environmental effects • Scientific correlation between used data and environmental assessment • Strong link between used data and results • Collection and processing of data is consistent with intention of result
Methodological completeness	Enables analysis of whole life cycle	• Method targets all major life cycle phases
	Method is defined for: system boundary	• Procedure for setting the boundaries(which stages, processes and flows are to be included) • Definition of cut-off criteria
	Method is defined for: multifunctional situations	• Possible ways for dealing with the topic are described • Priorities are set, with favour to scientific procedure
	Method is suitable for comprehensive environmental assessment	• The means to display differentiated & comprehensive picture of impact situation, covering natural resources, human health and ecosystem quality • consideration of double counting • Procedures for impact assessment defined, incl. selection and modelling of categories • Appropriateness for studied question

Criteria	Sub-criteria	Aspects to be considered
Availability of software tools	Number of available tools	• Simplified tools (permitting conduction of entire study but having very limited adaptation options) • 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) • Tools covering regional differences
	Variation in licence models	• Free licenses increasing access for different user groups • Commercial licences enhancing the quality of supply through competition and long term support/development
Suitability for time specific models	Time series	• Data is updated in appropriate intervals • Minimal time lag between data collection and data provision • Continuous application is intended by the methodology • Time series are able to reflect true changes in environmental impact (no distortion/influence by other factors, as e.g. monetary ones)
	Future scenarios	• Indication/analysis of consequences of changes possible • Uncertainty of estimated future impacts • Data is adaptable to time focused evaluations and has good potential to be developed further • Availability of scenario modelling functions in software, Parameterization possible • Time as variable in the functional model
Data availability and accessibility	Data coverage of the whole life cycle	• Material extraction • Processing • Use phase • Recycling/disposal etc.
	Availability of inventory data for different regions	• Data available for different continents/industrial & trade areas • Data adaptable to region-related evaluations

Criteria	Sub-criteria	Aspects to be considered
	Availability of inventory data for all relevant impact categories	- Global warming, - Acidification - Human toxicity - Ozone layer depletion - Eutrophication
	Publicly accessible inventory databases at affordable cost	- Free databases - Non-profit databases - Commercial databases
Data quality	Data characteristics	- Independence of economic and environmental information - Originally intended level of resolution (micro- or macro-level) is consistent with level of application
	Independent review	- Internal review - External/Third party review - Review procedure
	Data representativeness	- Time span - Source - Type of measurement - Technology coverage
	Data documentation	- data characteristics - representativeness aspects - review procedures - Transparent

Annex 2: Detailed quantitative results for the present and future evaluation

Table 55: Results for the life cycle method on the sub-criteria level for the present (p) and future (f) situation

Sub-criteria	Micro level perspective										Macro level perspective									
	P-LCA		EIO-LCA		MFA		EMC		Hybrid		P-LCA		EIO-LCA		MFA		EMC		Hybrid	
	p^1	f^2	p	f	p	f	p	f	p	f	p	f	p	f	p	f	p	f	p	f
Availability of guidelines or code of conduct	3	3	2	2	0	**1**	0	0	2	2	3	3	3	3	3	3	0	0	2	2
Detailed expert documentation	4	4	3	3	2	2	1	1	2	2	2	2	4	4	4	4	1	1	2	2
Comprehensible calculation and transparency	4	4	3	3	2	2	2	2	1	**2**	2	2	4	4	4	4	4	4	1	**2**
Availability of standardisation for method	4	4	1	1	0	0	0	0	2	2	2	2	1	1	0	0	0	0	2	2
Broad range of goods and services	4	4	3	3	2	2	2	2	4	4	4	4	3	3	2	2	2	2	4	4
Broad range of tasks	4	4	2	2	1	1	1	1	4	4	3	3	3	3	2	2	3	3	4	4
Inclusion of stakeholders	3	3	1	1	1	1	2	2	2	2	3	3	1	1	2	2	2	2	2	2
Method application by green and consumer NGOs		**1**		0		0		0		0		0		**1**		0		0		0
Method application by industry	4	4	1	**2**	1	**2**	0	0	1	**2**	1	**2**	1	**2**	3	3	0	0	0	**1**
Method application by policy makers	4	4	0	**1**	0	**1**	0	0	0	**2**	4	4	4	4	4	4	0	0	0	**2**

[1] p = present situation
[2] f = future situation

Sub-criteria	Micro level perspective										Macro level perspective									
	P-LCA		EIO-LCA		MFA		EMC		Hybrid		P-LCA		EIO-LCA		MFA		EMC		Hybrid	
	p[1]	f[2]	p	f	p	f	p	f	p	f	p	f	p	f	p	f	p	f	p	f
Reproducibility	3	3	4	4	3	3	3	3	3	3	3	3	4	4	3	3	3	3	4	4
Influence of assumptions	3	3	2	2	3	3	3	3	3	3	3	3	2	2	3	3	3	3	2	2
Clarity of method	3	3	1	**2**	2	2	2	2	1	**2**	2	2	3	3	4	4	4	4	1	**2**
Established communication	4	4	1	**2**	1	1	0	0	0	**2**	2	**3**	2	**3**	4	4	0	0	0	**2**
Scientific societies exist	4	4	4	4	3	3	0	0	4	4	4	4	4	4	3	3	0	0	4	4
Validation/ verification checks	4	4	2	2	2	2	0	0	2	2	3	3	3	3	3	3	1	1	3	3
Plausibility of results	4	4	1	**2**	2	2	2	2	3	3	2	2	2	**3**	3	3	3	3	3	3
Enables analysis of whole life cycle	4	4	2	2	4	4	4	4	4	4	4	4	2	2	4	4	4	4	4	4
Method is defined for: system boundary	2	**3**	3	3	1	1	1	1	2	**3**	1	1	3	3	4	4	4	4	3	3
Method is defined for: multifunctional situations	4	4	2	0	4	4	4	4	2	2	2	2	2	0	4	4	4	4	0	0
Method is suitable for comprehensive environmental assessment	3	3	2	2	0	0	3	3	3	3	3	3	2	**3**	0	**0**	3	3	3	3
Number of available tools	3	3	3	3	4	4	0	0	2	**3**	2	**3**	4	4	4	4	0	0	2	**3**
Variation in licence models	4	4	4	4	4	4	0	0	2	2	4	4	4	4	4	4	0	0	2	2
Time series	3	3	3	3	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3
Future scenarios	3	3	1	1	1	1	1	1	2	2	2	2	1	1	1	2	1	1	2	2

Sub-criteria	Micro level perspective										Macro level perspective									
	P-LCA		EIO-LCA		MFA		EMC		Hybrid		P-LCA		EIO-LCA		MFA		EMC		Hybrid	
	p[1]	f[2]	p	f	p	f	p	f	p	f	p	f	p	f	p	f	p	f	p	f
Data coverage of the whole life cycle	4	4	1	1	1	1	1	1	4	4	2	2	3	3	4	4	4	4	4	4
Availability of inventory data for different regions	3	3	1	**2**	3	3	3	3	3	3	2	**3**	2	**3**	3	3	3	3	3	3
Availability of inventory data for all relevant impact categories	4	4	2	**3**	3	3	4	4	3	3	4	4	2	**3**	3	3	4	4	3	3
Publicly accessible inventory databases at affordable cost	2	**3**	2	2	2	2	2	2	2	**3**	4	4	4	4	4	4	4	4	4	4
Data characteristics	4	4	1	1	2	2	2	2	3	3	1	1	2	2	4	4	4	4	3	3
Independent review	4	4	4	4	0	0	0	0	4	4	4	4	4	4	2	2	2	2	4	4
Data representativeness	4	4	1	1	2	2	2	2	3	3	3	3	3	**4**	2	3	3	3	3	3
Data documentation	4	4	2	2	3	3	3	3	3	**4**	3	3	3	**4**	3	3	3	3	3	**4**

Annex 3: Weighting Scheme

A weighting scheme was developed by the JRC IES in parallel to the evaluation in order to emphasize specific criteria and evaluate their impact on the overall evaluation. The weighting scheme is applied on the level of the sub-criteria.

The multiplying factors are the average results from 3 judgements of JRC IES experts. A 5-level scale is applied to avoid that some criteria become negligible. It is also symmetric with the 5-level scoring applied to the characterisation of the single sub-criteria. The results from the evaluation are weighted according to the values provided. Factors for each sub-criterion are stated below.

Table 56: Weighting factors used for the additional weighted evaluation

Criteria	Sub-criteria	Weighting factor
Method documentation and transparency	Availability of guidelines or code of conduct	4
	Detailed expert documentation	4
	Comprehensible calculation and transparency	4
	Availability of standardisation for method	2
Applicability	Broad range of goods and services	3
	Broad range of tasks	4
Stakeholder acceptance	Inclusion of stakeholders	3
	Method application by green and consumer NGOs	1
	Method application by industry	2
	Method application by policy makers	3
Objectivity in application	Reproducibility	4
	Influence of assumptions	3
Communicability of methods	Clarity of method	4
	Established communication	1
Scientific soundness of the approach	Scientific societies exist	1
	Validation/ verification checks	3
	Plausibility of results	5
Methodological completeness	Enables analysis of whole life cycle	5
	Method is defined for: system boundary	3
	Method is defined for: multifunctional situations	3
	Method is suitable for comprehensive environmental assessment	5

Availability of software tools	Number of available tools	2
	Variation in licence models	1
Suitability for time specific models	Time series	4
	Future scenarios	2
Data availability and accessibility	Data coverage of the whole life cycle	4
	Availability of inventory data for different regions	3
	Availability of inventory data for all relevant impact categories	4
	Publicly accessible inventory databases at affordable cost	2
Data quality	Data characteristics	3
	Independent review	3
	Data representativeness	4
	Data documentation	3

Annex 4: Weighted results for the present and future situation

Table 57: **Weighted results for the life cycle method on the criteria level, sorted by level of scope situation**

Criteria	Micro perspective										Macro perspective									
	P-LCA		EIO-LCA		MFA		EMC		Hybrid		P-LCA		EIO-LCA		MFA		EMC		Hybrid	
	p^3	f^4	p	f	p	f	p	f	p	f	p	f	p	f	p	f	p	f	p	f
Method documentation and transparency	52	52	34	34	16	20	12	12	24	28	32	32	46	46	44	44	20	20	24	28
Applicability	28	28	17	17	10	10	10	10	28	28	24	24	21	21	14	14	18	18	28	28
Stakeholder acceptance	29	30	5	10	5	10	6	6	8	16	23	25	17	20	24	24	6	6	6	14
Objectivity in application	21	21	22	22	21	21	21	21	21	21	21	21	22	22	21	21	21	21	22	22
Communicability of methods	16	16	5	10	9	9	8	8	4	10	10	11	14	15	20	20	16	16	4	10
Scientific soundness of the approach	36	36	15	20	19	19	10	10	25	25	23	23	23	28	27	27	18	18	28	28

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[3] p = present
[4] f = future situation

Criteria	Micro perspective										Macro perspective									
	P-LCA		EIO-LCA		MFA		EMC		Hybrid		P-LCA		EIO-LCA		MFA		EMC		Hybrid	
Methodological completeness	53	56	35	35	35	35	50	50	47	50	44	44	35	40	44	44	59	59	44	44
Availability of software tools	10	10	10	10	12	12	0	0	6	8	8	10	12	12	12	12	0	0	6	8
Suitability for time specificmodels	18	18	14	14	10	10	10	10	12	12	12	12	14	14	14	16	14	13	16	16
Data availability and accessibility	45	47	19	26	29	29	33	33	41	43	38	41	34	41	45	45	49	49	45	45
Data quality	52	52	25	25	23	23	23	23	42	45	36	36	39	46	35	39	39	39	42	45
Total	**360**	**366**	**201**	**223**	**189**	**198**	**183**	**183**	**258**	**286**	**271**	**279**	**277**	**305**	**300**	**306**	**260**	**260**	**265**	**288**

Annex 5: Illustration of weighted results on criteria level

Figure 10: Weighted criteria results for all life cycle methods on the micro level perspective, present situation

Figure 11: Weighted criteria results for all life cycle methods on the micro level perspective, future potential
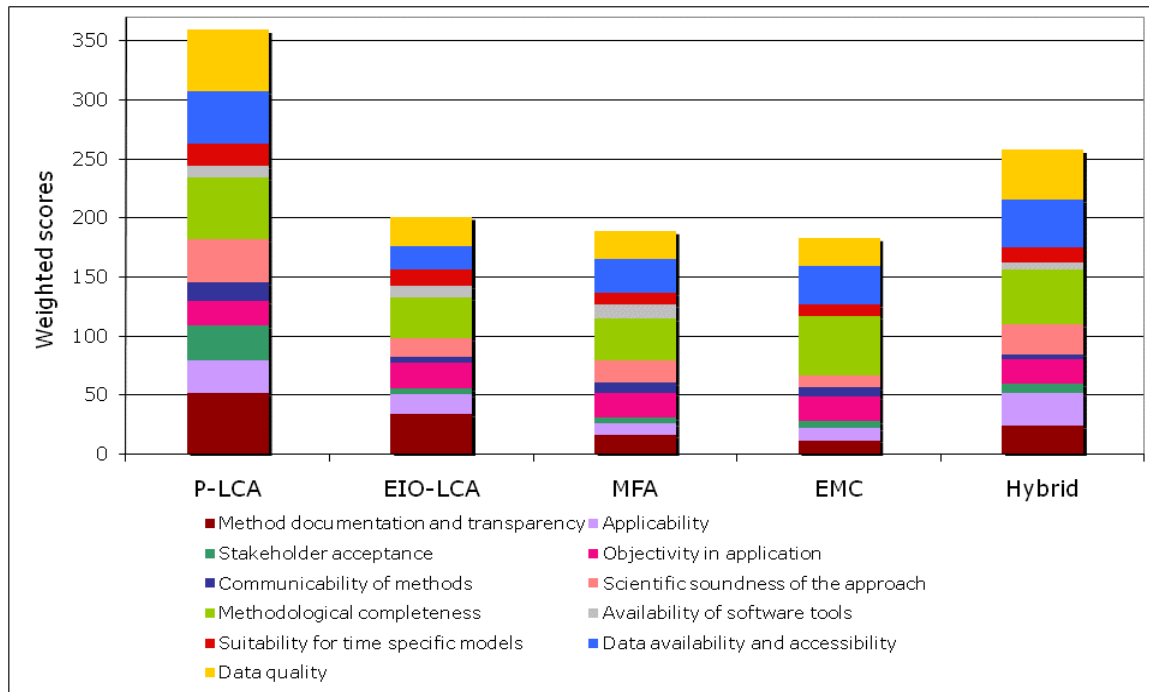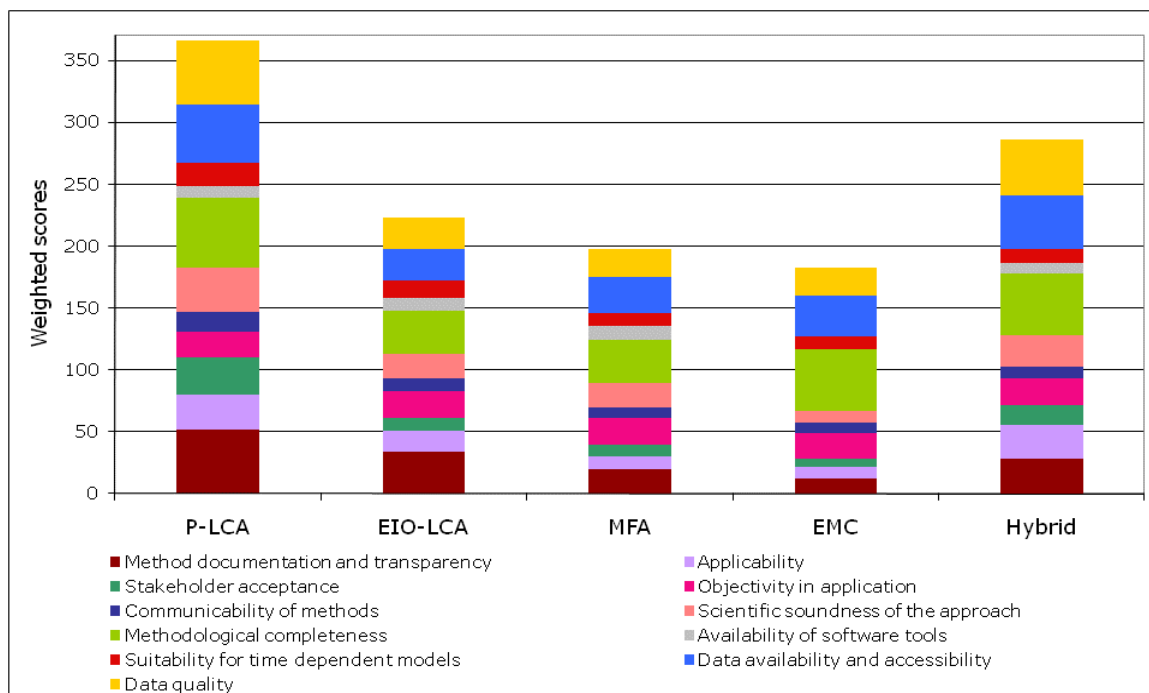
Figure 12: **Weighted sub-criteria results for all life cycle methods on the macro level perspective, present situation**

Figure 13: Weighted criteria results for all life cycle methods on the macro level perspective, future potential
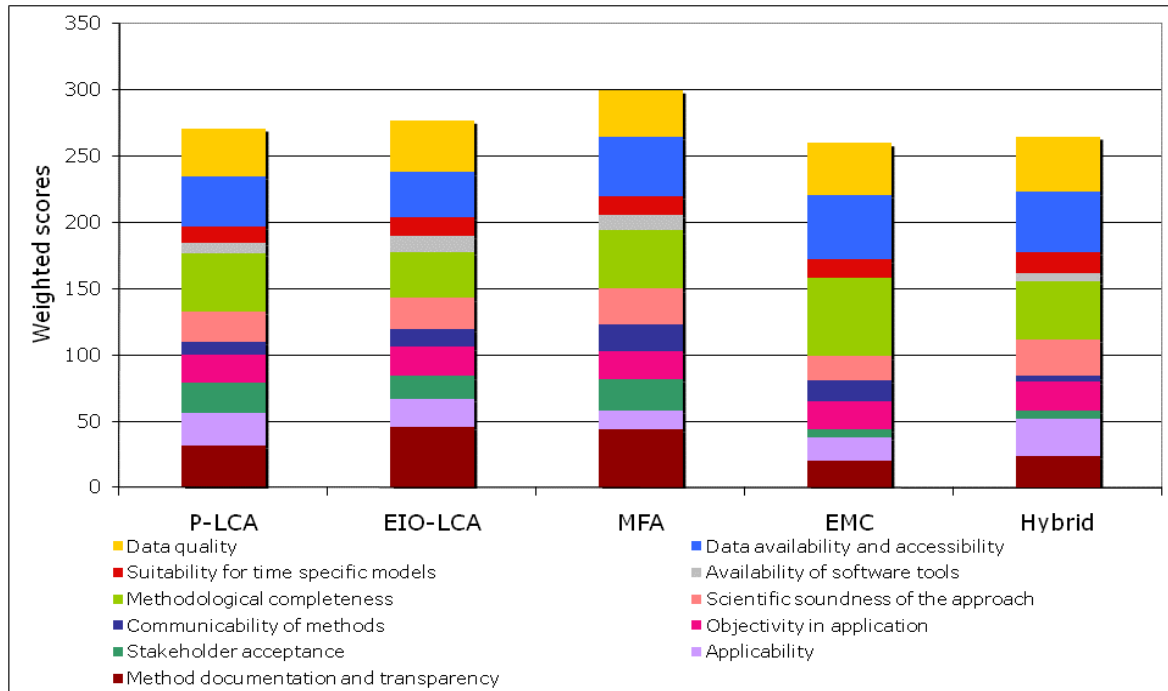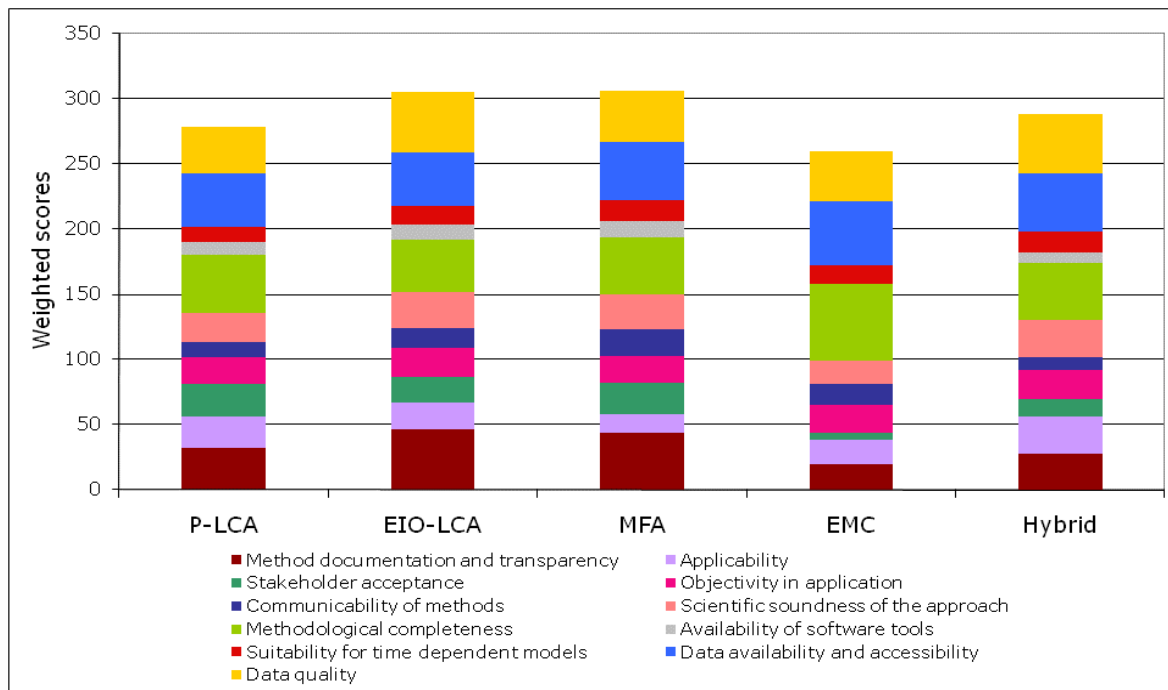
Annex 6: Evaluation of environmental life cycle approaches for their potential for waste management applications

Annex 6 focuses on the potential of process-based LCA (P-LCA), Hybrid LCA, Material Flow Analysis (MFA) and Environmental weighted Material Consumption (EMC) for applicability in waste management, as a complement to the report "evaluation of environmental life cycle approaches for policy and decision making support in micro and macro-level applications". This annex should only be distributed together with the main report, it is not a stand-alone document. The evaluation follows the same principles given in the general introduction (Chapter 1).

A6.1 Introduction

The issue in question here is the suitability of the methods to support decision making in waste management, i.e. to analyse the consequences of sector or region specific regulations on waste by comparing the environmental performance of different waste treatment scenarios. The evaluation is focused on solid waste. Thus the basis for the evaluation is the scores assigned on the macro level in the previous chapters. Not all scores assigned to the criteria in the previous evaluation are likely to change for this particular evaluation. Therefore, only those criteria for which differences can be discerned in comparison to the evaluation for a general application are discussed here. These differences do not necessarily have to be in the quantitative score, but can also be of a qualitative nature. The general evaluation is defined as a base evaluation. This means that the suitability of each method for a wide variety of possible applications is averaged in the given scores. The criteria identified (as to show significant differences for waste management applications in comparison with this averaged compliance of the methods) are described in this document. The unchanged scores from the general evaluation are stated as well.

In the general evaluation, a fifth method was considered in addition to the ones mentioned above: sector-based Economic Input-Output LCA. However, in pure Input-output analyses waste management issues (i.e. the decision whether a certain waste should be rather incinerated or recycled) cannot be addressed, because the existing IO tables do contain at the most two sectors for waste management, which do not allow for such detailed analysis. The IO tables in US and Japan are known to be the largest tables that are compiled and published on regular basis. The US table has one sector referring to waste management, while the Japanese table has two sectors distinguished by institutional factors only (public or private), containing no information about the physical flows. **EIO-LCA** will therefore be **excluded** from this waste-oriented analysis.

For P-LCA, MFA, EMC and the Hybrid approaches on the other hand applicability for waste management issues can be assumed in principle, they will therefore be evaluated here.

A6.2 Evaluation of the Life Cycle Methods

A6.2.1 General criteria

A6.2.1.1 Method documentation and transparency

Guidelines or code of conduct:

Reviewed guidelines for the use of LCA in waste management are available. The focus of these guidelines is on the Nordic countries but also includes developments for example in the UK. Important issues of the Nordic guidelines, which follow the structure of the ISO 14040, are system boundaries, inventory data, allocation and impact assessment [104]. However, the score in this case does not differ from the one in the general evaluation, as there is no compliance with the aspect of available commitments to apply the guidelines. Neither could be deduced in the research that the guidelines are widely applied without such commitment.

Guidelines for MFA in waste management were developed in the project "Aid in the Management of Municipal Solid WASte Treatment methods - AWASt" [105, 106]. As for P-LCA, there are no commitments to apply these guidelines; in addition their prominence is low as of now, which is why the score is unchanged.

Table 58: Quantitative evaluation for sub-criterion "guidelines or code of conduct"

P-LCA	MFA	EMC	Hybrid-LCA
3	3	0	2

Detailed expert documentation

Expert documentation for P-LCA and MFA consists of a great number of scientific papers as well as theses, both on the methods and different tools for their implementation. Literature research revealed no textbook or similar focussed specifically on waste management for these methods, apart from several documents related to P-LCA, partly related to available tools for LCA in waste management. Therefore, the average score from the general evaluation for P-LCA is put higher.

No documentation on waste management for EMC could be found. Thus the score is reduced by one point.

With the publication of Nakamura and Kondo on a model for waste input-output analysis and the linked there is comprehensive expert available and accessible for Hybrid LCA in the area of waste management which enhances the compliance of Hybrid LCA for this criterion [107, 108]. The availability of this documentation constitutes a considerable improvement shown in the higher score for Hybrid LCA, which is increased by one point.

Table 59:   **Quantitative evaluation for sub-criterion "detailed expert communication"**

P-LCA	MFA	EMC	Hybrid-LCA
3	4	1	2

Comprehensible calculation and transparency

There are no changes discernible for any of the methods with regard to this sub-criterion.

Table 60:   **Quantitative evaluation for sub-criterion "comprehensible calculation and transparency"**

P-LCA	MFA	EMC	Hybrid-LCA
2	4	4	1

Availability of standardisation for method

ISO series is applicable for using P-LCA for waste management too, as waste management is a service and as such incorporated in the term "product". Therefore, there are no changes discernible for any of the methods with regard to this criterion.

For MFA there is at least one national standard to be found which constitutes medium compliance with this sub-criterion.[109]

Table 61:   **Quantitative evaluation for sub-criterion "availability of standardisation"**

P-LCA	MFA	EMC	Hybrid-LCA
2	2	0	2

A6.2.1.2 Applicability

There are no changes discernible for any of the methods with regard to these sub-criteria.

Table 62:   Quantitative evaluation for sub-criterion "broad range of goods and services"

P-LCA	MFA	EMC	Hybrid-LCA
4	2	2	4

Table 63:   Quantitative evaluation for sub-criterion "broad range of tasks"

P-LCA	MFA	EMC	Hybrid-LCA
3	2	3	4

A6.2.1.3 Stakeholder acceptance

Inclusion of stakeholders

There are no changes discernible for any of the methods with regard to this sub-criterion.

Table 64:   Quantitative evaluation for sub-criterion "inclusion of stakeholders"

P-LCA	MFA	EMC	Hybrid-LCA
3	2	2	2

Method application by industry

P-LCA has been applied for waste management decisions in the past, though compliance with the ISO series was not necessarily existent. There are several examples of cooperation between research centres, waste companies and public institutions aiming at identifying, by LCA modelling, the best waste treatment option. For instance, the LCA model EASEWASTE [100, 110, 111], developed by the Technical University of Denmark has been extensively used to optimize waste management in some Danish municipalities and waste treatment facilities [112]. There also seem to be examples of applications by the major waste handlers, though they are often used internally and results are typically not made available to the outside world. Michel Dutang, director of research at Veolia Environnement claimed for instance, that LCA is used "almost always" to determine environmental impacts of new processes [113]. BRGM on the other hand is involved in various projects

concerned with the application of LCA for waste management, indicating their willingness to apply LCA [114].

MFA is used by industry for waste application, and there might be a slightly increased usage in comparison to the general evaluation. Again, this is indicated by the involvement of BRGM in research concerned with the method [114]. However, as the second aspect of the sub-criterion, the availability of commitments is not fulfilled and a score showing complete compliance is not justified.

For EMC and Hybrid-LCA there are no changes in comparison with the general evaluation.

Table 65:   **Quantitative evaluation for sub-criterion "method application by industry"**

P-LCA	MFA	EMC	Hybrid-LCA
1	3	0	0

Method application by policy makers

P-LCA has been applied as a decision- support tool for waste management in a number of studies. Several countries use LCA in their waste management. The US EPA, for instance, applies its own decision support tool, the MSW-DST [115-117], and has recently carried out a comprehensive study for the future waste management of the state of Delaware [118]. UK policy is taking the LCA idea even further. The UK Environment Agency recommends strongly the use of its LCA tool WRATE for option appraisal waste management in the Waste Infrastructure Delivery Programme [119-121]. On a local level there are examples from Denmark, where LCA has been used as the decision-support tool for the assessment of solid waste systems, e.g. in the municipality of Aarhus [112]. As in the general evaluation, compliance of the method with this sub-criterion is evaluated as complete.

MFA can supply the necessary information only under specific objective settings, if the targeted application is a tool for the aid of decision-making as to which waste treatment way is preferable. This depends on the goal of MFA study. For instance, if the goal is to determine how materials reach their final destinations (e.g. landfill, incineration, dissipation into environment, etc.) MFA cannot be used for selecting alternative waste management scenarios. In this sense, MFA has been used for waste management applications by policy makers just as it was found for the general evaluation (see for example the Austrian study on alternative waste scenarios [122]). The method can be used to measure effects of legislative measures, but also to calculate the composition and the amount of wastes. Due to the limited applicability

and dependency on the goal, compliance of the method with this sub-criterion is reduced to essential.

The WIO model has been applied on a municipal level at least once [123]; compliance is therefore low but existent for Hybrid LCA.

EMC has not been applied yet by policy makers.

Table 66: **Quantitative evaluation for sub-criterion "method application by policy makers"**

P-LCA	MFA	EMC	Hybrid-LCA
4	3	0	1

A6.2.1.4 Objectivity in application

The objectivity of a method is not dependent on the field of application. Therefore, there are no changes here in comparison to the general evaluation.

Table 67: **Quantitative evaluation for sub-criterion "reproducibility"**

P-LCA	MFA	EMC	Hybrid-LCA
3	3	3	4

Table 68: **Quantitative evaluation for sub-criterion "influence of assumptions"**

P-LCA	MFA	EMC	Hybrid-LCA
3	3	3	2

A6.2.1.5 Communicability of methods

Clarity of method

There are no changes discernible for any of the methods with regard to this sub-criterion.

Table 69: **Quantitative evaluation for sub-criterion "clarity of method"**

P-LCA	MFA	EMC	Hybrid-LCA
2	4	4	1

Established communication

For MFA compliance is lower than for the general evaluation, as there are no specific communication experiences in waste management applications. However, communication methods used generally may still be applied to some extent. For P-LCA existing communication methods like Environmental Product Declarations (EPDs) are only starting to be used also for waste related topics such as landfills. There are no changes for Hybrid-LCA and EMC compared to the general evaluation.

Table 70:   Quantitative evaluation for sub-criterion "established communication"

P-LCA	MFA	EMC	Hybrid-LCA
1	3	0	0

A6.2.2 Methodological criteria

A6.2.2.1 Scientific soundness of the approach

The scientific soundness of a method is not dependent on the field of application. Therefore, there are no changes here in comparison to the general evaluation.

Table 71:   Quantitative evaluation for sub-criterion "existence of scientific societies"

P-LCA	MFA	EMC	Hybrid-LCA
4	3	0	4

Table 72:   Quantitative evaluation for sub-criterion " validation/ verification checks"

P-LCA	MFA	EMC	Hybrid-LCA
3	3	1	3

Table 73:   Quantitative evaluation for sub-criterion "plausibility of results"

P-LCA	MFA	EMC	Hybrid-LCA
2	3	3	3

A6.2.2.2 Methodological completeness

Enables analysis of whole life cycle

There are no changes discernible for any of the methods with regard to this sub-criterion.

Table 74: Quantitative evaluation for sub-criterion "Enables analysis of whole life cycle"

P-LCA	MFA	EMC	Hybrid-LCA
4	4	4	4

Method is defined for: system boundary

There are no changes discernible for any of the methods with regard to this sub-criterion.

Table 75: Quantitative evaluation for sub-criterion "Method is defined for: system boundary"

P-LCA	MFA	EMC	Hybrid-LCA
1	4	4	3

Method is defined for: multifunctional situations

The WIO model deals with allocation issues in waste treatment applications, possible approaches are described. This is not necessarily universally valid. The compliance of the Hybrid LCA with this sub-criterion is therefore rated as medium.

Compliance for P-LCA, EMC and MFA does not differ from the general evaluation.

Table 76: Quantitative evaluation for sub-criterion "Method is defined for: multifunctional situations"

P-LCA	MFA	EMC	Hybrid-LCA
2	4	2	2

Method is suitable for comprehensive environmental assessment

There are no changes discernible for any of the methods with regard to this sub-criterion.

Table 77:   **Quantitative evaluation for sub-criterion "Comprehensive environmental assessment"**

P-LCA	MFA	EMC	Hybrid-LCA
3	0	3	3

A6.2.3 Technical criteria

A6.2.3.1 Availability of software tools

Number of available tools

General P-LCA software tools are often not sufficient for waste management applications as their information for waste is not detailed enough. Tools specific to waste management exist, both simplified as well as expert tools, e.g. "LCA-IWM" or "EASEWASTE". These waste related models usually show a regional dependency, which means that in contrast to the general evaluation, regional differences are better covered. Different LCA tools that can be applied to waste management are listed here, indicating their providers, their level of expertise and information on included data. A more comprehensive overview of waste management related LCA tools can be found in [116, 124].

LCA-Tools applicable to waste management:

- EASEWASTE (DTU Denmark). The expert tool is flexible. It uses Danish and European data; data can be adjusted by the user. The focus of the tool is on household waste [100, 110-112, 116, 124].

- LCA – IWM (TU Darmstadt). The tool is excel-based and simply structured. Its flexibility is limited. It includes extensive data from direct research and literature; data is focused on the European situation [116, 124, 125].

- IWM Canada (EPIC/CSR). The tool is excel-based and simply structured. Its flexibility is limited. It includes data from Canadian industry and the US EPA, the emission factors are outdated [116, 124].

- Integrated Waste Management 2 (Procter & Gamble). The tool is clearly structured, yet flexible and adaptable. It includes extensive data from literature on emissions and costs, as well as treatment processes and collection systems, but the data access is limited. The focus is on developing countries [116, 124, 126].

- ORWARE (Swedish EPA): This expert tool is based on MatLab and flexible. It combines the concepts and tools of MFA LCA and Life Cycle Costs (LCC). Data include various waste treatment processes and stems mainly from own research [116, 124, 127].

- GABI (PE International). It is an expert tool, which is not waste specific. Databases are very comprehensive and include an additional database specific for waste management [116, 128]

For MFA no specific software tools are available, though generic ones may still be used to some extent as it was stated in the general evaluation. ORWARE, as mentioned above, includes an MFA approach [116].

At the moment there are no software tools which include waste input-output data as might be used in Hybrid LCA. As in general there are no software tools for EMC.

Table 78: Quantitative evaluation for sub-criterion "number of available software tools"

P-LCA	MFA	EMC	Hybrid-LCA
4	2	0	0

Variation in licence models

Different licence models are available within the supply of waste specific P-LCA tools [116].

Both free and commercial software tools are available for MFA, though only as generic software, not waste specific.

At the moment there are no software tools which include waste input-output data as might be used in Hybrid LCA.

Table 79: Quantitative evaluation for sub-criterion "variation in licence models"

P-LCA	MFA	EMC	Hybrid-LCA
4	3	0	0

A6.2.3.2 Suitability for time specific models

There are no changes discernible for any of the methods with regard to these sub-criteria.

Table 80: **Quantitative evaluation for sub-criterion "time series"**

P-LCA	MFA	EMC	Hybrid-LCA
2	3	3	3

Table 81: **Quantitative evaluation for sub-criterion "future scenarios"**

P-LCA	MFA	EMC	Hybrid-LCA
2	1	1	2

A6.2.4 Data criteria

A6.2.4.1 Data availability and accessibility

Availability of inventory data for the whole life cycle

Data necessary for the modelling of waste management systems includes system and process data. The process data (incineration specifics, flue gas effectiveness) is usually available, also through existing databases. Data on waste composition and transport for waste collection can often be difficult to obtain, as they cannot be provided by generic databases but rather need to be collected case specific [124]. This limitation, however, affects all considered methods.

Availability of data in this case is understood as availability of data for the end-of-life phase. On this assumption data is in principle available for all considered methods.

Table 82: **Quantitative evaluation for sub-criterion "availability of inventory for the whole life cycle"**

P-LCA	MFA	EMC	Hybrid-LCA
4	4	4	4

Availability of inventory data for different regions

Waste input-output data covering different regions are still scarce; the compliance of the Hybrid LCA is therefore lower than in the general evaluation.

For P-LCA, in various countries region specific data is available, e.g. for Denmark, Nordic countries, the UK, France and Germany. Therefore the score is as high as for MFA and EMC. However, it has to be noted that the data tends to be scattered around and is not easily accessible.

The other methods show no difference in comparison to the general evaluation.

Table 83: **Quantitative evaluation for sub-criterion "availability of inventory for different regions"**

P-LCA	MFA	EMC	Hybrid-LCA
3	3	3	2

Availability of inventory data for all relevant impact categories

There are no changes discernible for any of the methods with regard to this sub-criterion.

Table 84: **Quantitative evaluation for sub-criterion "availability of inventory for all relevant impact categories"**

P-LCA	MFA	EMC	Hybrid-LCA
4	3	4	3

Publicly accessible inventory databases at affordable cost

P-LCA related data concerned with waste is incomplete and only available in general databases which lack detail in regard to waste issues or tool-related (such as a database with Danish waste data included in the EASEWASTE model [129]). Waste input-output databases are also scarce; the compliance of the Hybrid LCA is therefore lower than in the general evaluation and only P-LCA related data can be assumed available to a significant extent. MFA and EMC databases is considered essential with the availability of general databases as their focus on substances inherently causes them to be suitable for waste management questions.

Table 85: **Quantitative evaluation for sub-criterion "publicly accessible inventory databases at affordable cost"**

P-LCA	MFA	EMC	Hybrid-LCA
2	3	3	2

A6.2.4.2 Data quality

Data characteristics

There are no changes discernible for any of the methods with regard to these sub-criteria

Table 86:   **Quantitative evaluation for sub-criterion "data characteristics"**

P-LCA	MFA	EMC	Hybrid-LCA
1	4	4	3

Independent review

There are no changes discernible for any of the methods with regard to this sub-criterion

Table 87:   **Quantitative evaluation for sub-criterion "independent review"**

P-LCA	MFA	EMC	Hybrid-LCA
4	2	2	4

Data representativeness

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. Due to the variety of different databases and tools available for waste applications in P-LCA it can well be differentiated between the different waste treatment technologies. On average, the tools cover the currently available technologies, taking into account regional differences as waste related LCA tools are usually region dependent e.g. landfilling, different types of material and energy utilization as well as thermal treatment [116, 124, 129]. Some restrictions apply due to dependency on statistical data which is why the score for essential compliance is applied.

Provision of data for waste management applications of MFA is still a challenge and often needs to be done on a case-by-case basis. However, if MFA is to be applied to waste management, suitable data can be obtained either by direct or by indirect analyses [56]. For the current situation the overall representativeness of MFA data is therefore evaluated as showing medium compliance only.

The reasoning for EMC in this sub-criterion is the same as for MFA.

For Hybrid LCA representativeness cannot readily be assumed as models applicable for waste management are scarce and have mainly been developed for exemplary applications. For these examples representativeness in source, technology coverage, time span etc. is given as data is collected directly, but since there is not enough data yet to justify generalisation the scoring here is reduced in comparison to the overall evaluation.

Table 88:   **Quantitative evaluation for sub-criterion "data representativeness"**

P-LCA	MFA	EMC	Hybrid-LCA
3	2	2	2

Data documentation

Data used in the considered P-LCA software tools is mostly documented well [116, 130], but in some cases no explicit information about required or factual documentation is available [116, 131]. The rating is therefore essential, not complete compliance.

For MFA (and also EMC) data documentation is very case specific. It ranges from being well documented [122] to inaccessible [132]. As an average the data documentation of MFA (and EMC) waste date is therefore rated medium.

For Hybrid LCA documentation of data is limited as the data itself is limited. The comprehensive WIO table compiled for Japan [108] is based on Japanese statistical data and well documented. Due to the lack of actual data, compliance will be rated only essential, not complete, as more case studies would be needed for a more comprehensive evaluation.

Table 89:   **Quantitative evaluation for sub-criterion "data documentation"**

P-LCA	MFA	EMC	Hybrid-LCA
3	2	2	3

A.6.3 Applicability of the Life Cycle Methods for waste management

Looking at the overall evaluation of the considered methods applications, it can be stated that P-LCA and MFA show an equal suitability for applications related to waste management, see Figure 14 and Figure 15.

P-LCA is well suitable for a use in waste management as system comparisons are possible and databases are adaptable to different objectives and situations. However, the method is seen as having limitations with regard to its applicability in waste management by different authors, the most severe of which are the missing time dimension in the evaluation, the missing local disaggregation and the issue of allocation or crediting [124, 133, 134]. However, as these are known limitations in all LCA applications and are therefore already taken into account in the general evaluation, they are not taken into consideration here for the quantitative evaluation. No independent assessment of the specific importance of these limitations for waste management could be found. Related to waste management, P-LCA shows better compliance with the criteria of software and data availability as well as stakeholder acceptance while its communicability decreases. A weak point for P-LCA remains the communicability of results which seem to reflect the inherently complex approach of LCA to cover a broad range of environmental impacts, looking at a large number of processes over different time horizons and across the globe.
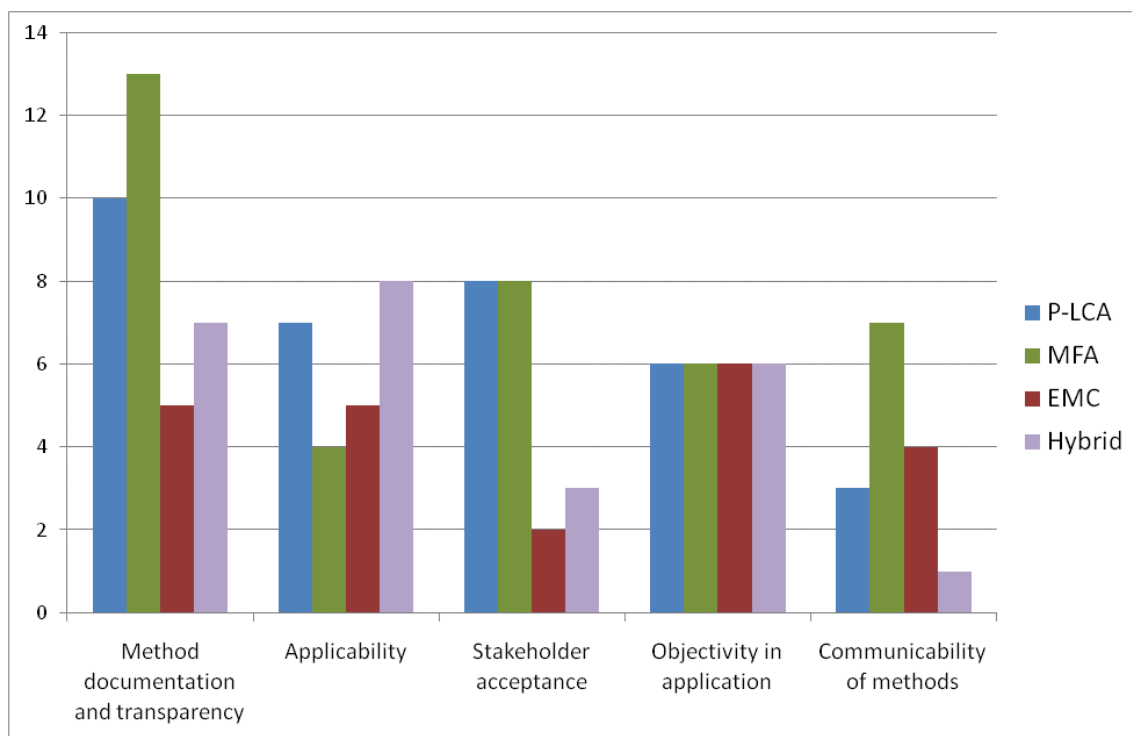

Figure 14: Quantitative results of the methods in the general criteria for waste management applications

This last point of communicability is exactly the strong point of MFA with regard to waste as is the method documentation and transparency which increases in comparison to the general evaluation. The compliance of MFA with methodological completeness is also better than the one of P-LCA. On the other hand lower compliance is shown in overall applicability and the availability of software tools.

The results also highlight that EMC and Hybrid LCA fall behind mainly due to the limited availability of software tools, stakeholder acceptance and method documentation and transparency. Data availability and documentation are lower than for the general evaluation.

The data basis for the EMC inventory side is national material flow accounts. In the current level of method development it may be useful for monitoring applications in the waste management sector but for the same reasons as MFA under specific goals. Wider consequences of alternatives can be conveyed due to the added environmental assessment. However, information on EMC for the use in waste management is missing at the moment, which leads to a reduced compliance with the criterion of method documentation and transparency. Its suitability cannot be evaluated comprehensively due to a lack in waste management specific information on EMC. The method needs to be described and discussed further in order to get a clearer picture.
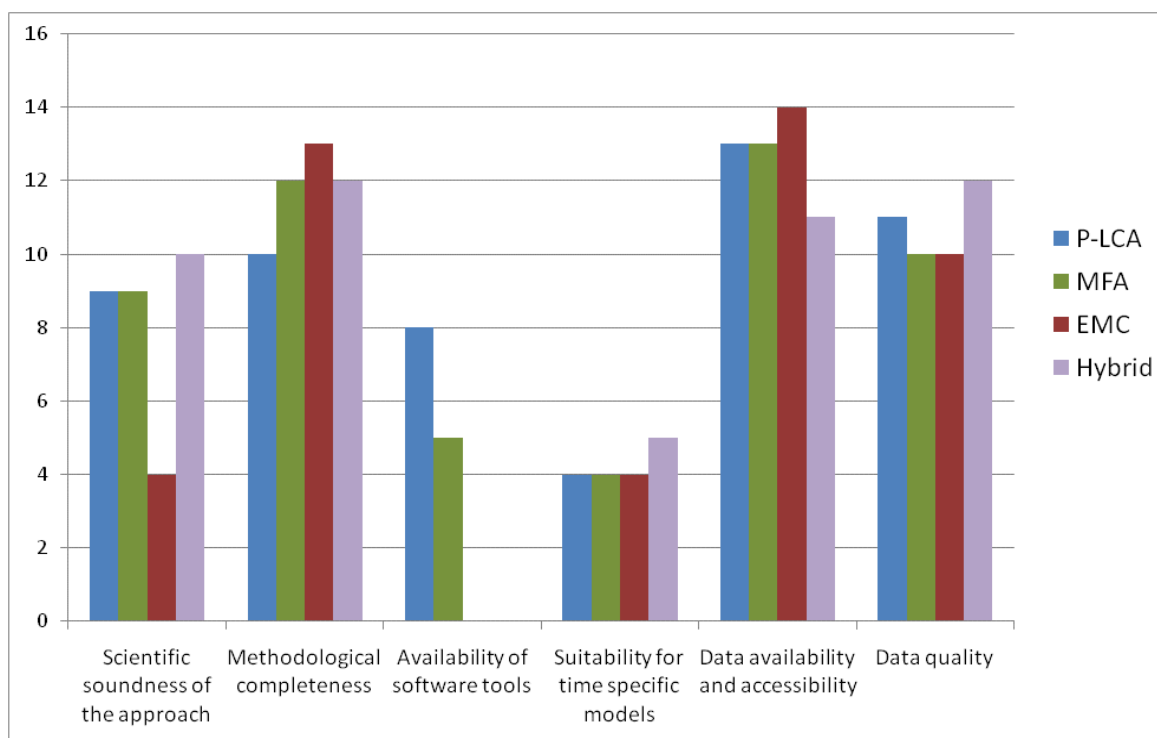
Figure 15: Quantitative results of the methods in the specific criteria for waste management applications

In summary it can be said with regard to the application of the selected methods to the waste management sector that P-LCA and MFA are both equally suitable, with different advantages and disadvantages. EMC and Hybrid approaches do not perform as well as P-LCA and MFA, mainly due to the limited availability of software tools, stakeholder acceptance and method documentation and transparency.

Annex 7: Peer Review

This annex gives the complete list of the peer review comments and indications on how they have been considered. The numbering of the headings follows the structure of the main report.

General comments

No 1.

Authors and overall quality of the report

Three well-reputed scientists, with the support of a young research assistant, have prepared the report under review. All the authors have published scientific papers in the field of LCA; Prof. Arpad Horvath is one of the developers of EIO-LCA; Prof. Matthias Finkbeiner is also very active in ISO standardisation of LCA; Prof. Yasunari Matsuno's main research field, according to his own description in the faculty web site, is the integration of LCA with population balance model (PBM) and material pinch technology but he also co-authored some publications on MFA.

The report is very well written, with clear and unambiguous style. The study has been conducted in a professional manner, with high competences and respecting the mandate.

(Masoni)

Noted.

No 2.

Question to be answered by the report

As first comment, I think that the main question at the basis of the report could have been better defined. Indeed, in the Term of Reference for my review (Anonymous 2010) is stated:

The study analyses different life-cycle methods and provides <u>an evaluation of their suitability in micro level and macro level situations</u>. The micro level perspective is typically connected to situations of decision making concerning a single product, process, technology or site. The macro level perspective is focussed on national or international policy making, for instance through monitoring the impacts of production and consumption at the level of EU or Member States.

In my opinion, the classification of the sustainability decision question in just "micro" and "macro" level should be further detailed. For example, the Draft International Reference Life Cycle Data System (ILCD) Handbook: General guidance document for Life Cycle Assessment (LCA) lists more than 15 applications for LCA as the most frequently used ones. The same document proposes a classification in four classes of the different decision situation contexts.

A decision situation at micro level (for instance: a study on the environmental effects of a single technology with a potential of large interactions with the rest of the economy) can lead to macro level effects that you may be interested to assess. The discussion on biofuels is a typical example. Or you may be interested only on the micro level consequences, as for example in marketing a "green" product. Monitoring the progress in decoupling is an example of situation of interest on macro effects at macro level, but you may also be interested in understanding the effects of a single product on those macro results, etc. So, the spectrum of sustainability

decision situations can be very broad. One method can be very suitable for a specific case but not for others.

For a comprehensive discussion of this issue, please refer to Deliverables D20 (Zamagni et al 2009a) and D22 (Guinée et al 2009) of CALCAS project, www.calcasproject.net .

Another important question, not explicitly asked in the term of reference, is:

"It is more recommendable to have a toolbox of specialised tools or a single tool that is capable to address more or less all the situations?"

In the report, in developing the scoring methodology is implicitly assumed as preferable the latter option. I do not agree with this implicit assumption.(Masoni)

Accepted with modification. A list of applications will be added. Overall evaluation is not in conflict with toolbox idea and was requested in the tender.

No 3.

Missing specification of the study's main objective. The study does not clearly state at the very beginning that the evaluation of methods is oriented towards environmental impacts, i.e. that methods rank higher, if they inherently include an environmental impact assessment. The reviewer suggests that in the section on "project goal and scope" in the executive summary as well as in the "introduction" of the main text, the authors clarify that the main objective of this study is to identify methods, which allow assessing environmental *impacts.* The authors should then also explain, why MFA was still considered as a potential method, when MFA is being well-known as a method designed for reflecting environmental *pressures*, not impacts. Only at the very end of the study (Chapter 9), the authors explain the special status of MFA in this study. This explanation should be provided upfront. (Giljum)

Accepted with modification

No 4.

Better coverage of micro applications than of macro applications. The authors apparently have their focus on a micro-perspective throughout the study and do not sufficiently separate micro-oriented from macro-oriented applications within the five groups of methods. This is particularly visible for the two methods of EIO-LCA and MFA. In the chapter on EIO-LCA, the authors mix applications of environmentally-extended input-output analysis (EE-IOA), i.e. IO applications, which do not use LCA components, with those IO approaches, which integrate LCA-based procedures (EIO-LCA).. Regarding this method, the reviewer suggests to focus the chapter only on EE-IOA and integrate the EIO-LCA applications into the chapter of Hybrid Approaches (see next paragraph for details). Also regarding MFA, the authors have a bias towards the micro perspective, i.e. Substance Flow Analysis (SFA). The reviewer suggests including more detailed information and a broader set of recent literature on economy-wide MFA in the description and evaluation of Material Flow Analysis (see the MFA-related chapters below for detailed suggestions). (Giljum)

Accepted with modifications.

No 5.

Missing evaluation of input-output approaches and overlaps between methods. The method of EIO-LCA is not described and evaluated consistently in the study. In chapter 2.2, which describes EIO-LCA, the authors mix approaches of environmentally-extended input-output analysis (EE-IOA), i.e. "pure" input-output analysis without LCA-based modifications, with EIO-LCA, which includes LCA-

based elements. The authors mention Wassily Leontief as the founder of input-output analysis, but in the next sentence turn immediately to the developers of EIO-LCA. The authors thus miss taking into account the dynamic development of EE-IOA and the large spectrum of new applications of EE-IOA in the past few years. Moreover, the EIO-LCA has clear and large overlaps with the Hybrid Approaches, which the authors also acknowledge: "*Overall, the EIO-LCA is therefore equivalent to the method usually referred to as basic hybrid approach*" (p. 22). From the reviewer's perspective it is not justified keeping the method EIO-LCA as a separate method in addition to the Hybrid Approaches in this study. The reviewer therefore suggests focusing on EE-IOA in the input-output chapters of the report and properly evaluating the strengths and weaknesses of EE-IOA in contrast to EIO-LCA/Hybrid Approaches. (Giljum)
Noted. Terminology will be clarified.

No 6.

Adopted methodology
The evaluation of the five different Life Cycle based assessment methods has been conducted with a scoring system. A superficial reader could misinterpreted the final numerical results as "objective" when, on the contrary, the evaluation is based on a subjective expert judgement, where the scoring system on a large number of criteria is just a framework to provide transparency and balance in the process.
My preference, in similar situation, is towards qualitative approaches (as, for example, with a SWOT analysis).Masoni)
Noted SWOT is definitely a possibility, but the tender was based on a scoring approach.

No 7.

Clear structure and transparent evaluation scheme. The study has a clear overall structure and the sequence of chapters is well chosen. The elaboration of the comprehensive evaluation scheme for comparing the different methods is transparent and allows tracing back aggregated evaluation results to single criteria, which is of high importance for evaluation studies of this type. Also the applied weighting scheme is transparent. The three Annexes provide important synthesised information on the overall results of the study. (Giljum)
Noted.

No 8.

Chapter 3 develops and describes a comprehensive scheme of criteria to evaluate the suitability of the different methods for providing life-cycle wide environmental assessments. The evaluation scheme is fully transparent and well illustrated in Annex 1. It is particularly valuable that in Annex 1, the authors provide a column with "aspects to be considered" for each of the sub-criteria. This allows closely corresponding the requirements in each sub-criterion with the allocated scores. The review has no specific suggestions to include further criteria in the evaluation scheme. If the scoring is done consistently, the scheme is effective to meet the project goals. (Giljum)
Noted

No 9.

Generally speaking, the adopted method is suitable to provide a framework for expressing in a transparent way an expert judgment. Personally, I am quite cautious

in adopting a quantitative scoring in subjective judgements, as "numbers" are generally interpreted as "more precise" and "more reliable" that a qualitative sentence.

CALCAS project performed a detailed Strengths Weaknesses Opportunities and Treats analysis (SWOT) of more than 30 methods/procedures, including four out five of the methods here studied. The document (Schepelmann et al 2008) reports the results of the SWOT analysis and, in my opinion, is a valuable contribution towards the stated objective of this study.(Masoni)

Noted. SWOT is definitely a possibility, but the tender was based on a scoring approach.

No 10.

Scoring should be consistent and based on most recent literature. The reviewer acknowledges the fact that scoring always includes subjective elements, even if scores reflect the opinion of several experts. The reviewer also made this experience in similar studies, which evaluated methodologies suitable for the assessment of environmental impacts related to resource use [see 135] and the assessment of environmental impacts embodied in international trade [136]. From an overall perspective, the scoring exercise in the study revealed plausible results, although the reviewer addresses a number of detailed issues, where the scoring is not fully consistent or where recent developments have not been taken into account. Therefore, the reviewer included comments on the scoring in several sections of chapter 5. (Giljum)

Noted.

No 11.

Scores should be based on actual practice in the application of methods, not on intentions. In several parts of the scoring exercise, it is unclear, whether the authors provide high scores on the basis of potentials and intentions of a methodology or on the implementation of these intentions in practical work. (Giljum)

Noted. For specific examples mentioned in this comment see later on.

No 12.

The references in several chapters of the study are outdated. A large part of the literature cited in the study was published around the year 2000, or even earlier. This is particularly notable in chapter 2, where the state of the art of the different approaches is described and current methodological gaps are identified. The authors seem not to be fully aware of the very dynamic development in the related fields in the past 5 years, in particular regarding the methods EE-IOA, macro MFA and EMC. In order to improve the study, the authors should include more recent literature in chapter 2, which would also effect the scoring in some parts of chapter 5. The reviewer suggests selected literature for possible inclusion in the study in the reviews of the different chapters below. (Giljum)

Noted. References mentioned below will be checked.

No 13.

Vague language should be avoided. In several parts of the study, the authors use vague phrases. Examples include: "*Considered impact categories are not defined for EIO-LCA but there seems to be a focus on resource use, greenhouse gas*

emissions and toxicity" (p. 22). The authors should refer to recent literature in order to verify, whether this focus can actually be observed. Recent reviews of the EE-IOA and EIO-LCA methods include, among others: [137-140]. Another example: "*In general, there is a lack of data for both, process-based LCA as well as EIO-LCA, but perhaps not to the same extent*" (p. 36). The authors should substantiate, whether or not there is a difference in data availability. (Giljum)
Accepted.

Executive Summary

No 14.
The summary is well done, as the principal aspects of the reports are clearly summarised, providing also a description of the final results. (Masoni)
Noted.

No 15.
The executive summary is clearly structured and provides a good and comprehensive overview over the methodology and the results of the study. (Giljum)
Noted

1 Introduction

No 16.
As mentioned above the authors should clarify that the study aims at identifying methods, which allow life-cycle wide environmental *impact* assessments and not methods assessing environmental pressures (such as MFA).(Giljum)
Accepted with modification

No 17.
The introduction provides a concise background on the policy processes important for this study and the related ongoing work by JRC and EUROSTAT. (Giljum)
Noted

No 18.
Please refer to my first general comment in Part I. The report does not state how the 5 methods have been selected: I understand that they have been chosen by JRC IES, but this should be clearly stated in the report.(Masoni)
Accepted.

No 19.
Page 13: To the reviewer's knowledge, the EU SCP Action Plan was adopted in July 2008, not in 2009. (Giljum)
Accepted, modified.

No 20.
Page 15: The authors state that "*It is possible that some specific methods are more suitable for microlevel analysis, others for macro policy support, while in other situations method integration in the form of a hybrid approach could be the best solution.*" This is what many other studies reviewing environmental assessment methods have concluded [136, 140]. However, this study differs in its conclusions

stating that P-LCA is the best suitable-method for both the micro and the macro level. As stated already above and illustrated in detail in the review of chapter 5, the reviewer suggest revising some of the scores, in particular for macro applications of P-LCA. (Giljum)
Rejected, there is no statement that P-LCA is the best on macro.

2 Method description

No 21.

Chapter 2 provides a short description of each of the selected methods. The structure to describe the methods (methodological description, development, applications, gags and methodological research) is well chosen. However, several subchapters suffer from an imprecise separation between micro and macro developments. Furthermore, regarding several methods, recent developments in methodological improvement and standardisation have not been taken into account. (Giljum)
Noted

No 22.

General comment: it is not clear why the computational structure has been described only for MFA/SFA and not for all methods.(Masoni)
Accepted with modifications. MFA will be revised.

2.1: Characterisation of process-based LCA.

No 23.

In general, the authors seem to have a profound knowledge on P-LCA. (Giljum)
Noted.

No 24.

The basic modeling principles of P-LCA are not described.
LCA has been developed and standardized for evaluating the environmental potential impacts of goods and services, it usually applies a simple linear static model based on the technological relations of the product system and does not take into account the social and economic effects. LCA typically takes into account only technological and environmental relations in inventory and impact assessment phase respectively (Hejiungs et al. 2010), leaving any other mechanism out of considerations. This shall be made very clear as these characteristics have several consequences.
Paragraphs 2.1.4 and 2.1.5 are not comprehensive. Please refer to CALCAS deliverables D7 (Zamagni et al 2008) and D14 (Zamagni et al. 2009b) for an analysis of methodological gaps, present development trends and suggested future researches. In particular, all the researches on LCI and modeling are here not even mentioned.(Masoni)
Accepted with modification. The description of methods can be only an overview and not a comprehensive coverage but some of the mentioned aspects will be added.

2.1.4.1: **Methodological gaps**

No 25.

The reviewer agrees with many statements provided in this chapter regarding the missing standardisation regarding cut-off criteria and allocation procedures, which allow "*various interpretations with high impact on the results*". Furthermore, the authors rightly point to the fact that there is a "*missing connection to time and location*", i.e. that currently available impact factors are only rarely specific regarding space and time. However, the scores provided for P-LCA contradict these statements, as the authors state that P-LCA already today should receive full scores and can hardly be improved in the next 10 years.   (Giljum)
Rejected.

2.1.5.2: Foreseen development work
No 26.

The authors could include a reference to the CALCAS project here, where a number of issues related to further development and extension of LCA have been elaborated. (Giljum)
Accepted.

2.1.5.3: improvement in data basis
No 27.

The authors could mention other data improvement initiatives apart from the European platform. For example, to the reviewer's knowledge, the next version of the ecoinvent database (version 3) is intended to be published in 2012, containing a larger number of processes, impact factors and input-output data (see http://www.ecoinvent.org/ecoinvent-v3). (Giljum)
Rejected, the EC platform only mentioned as an example not a complete "list"

2.1.5.4: New application fields
No 28.

Also in this chapter, the authors could refer to and include some of the results from the CALCAS project [see, for example, 141]. (Giljum)
Accepted with modification, Reference should be added

2.2.: Characterisation of EIO-LCA

No 29.

Missing evaluation of input-output approaches and overlaps between methods. The method of EIO-LCA is not described and evaluated consistently in the study. In chapter 2.2, which describes EIO-LCA, the authors mix approaches of environmentally-extended input-output analysis (EE-IOA), i.e. "pure" input-output analysis without LCA-based modifications, with EIO-LCA, which includes LCA-based elements. The authors mention Wassily Leontief as the founder of input-output analysis, but in the next sentence turn immediately to the developers of EIO-LCA. The authors thus miss taking into account the dynamic development of EE-IOA and the large spectrum of new applications of EE-IOA in the past few years. Moreover, the EIO-LCA has clear and large overlaps with the Hybrid Approaches, which the authors also acknowledge: "*Overall, the EIO-LCA is therefore equivalent to the method usually referred to as basic hybrid approach*" (p. 22).
Accepted with modification, clarification will be done with expert.

No 30.

As described in Part I of the review above, the reviewer thinks that this chapter needs to be improved. To the reviewer's opinion, the authors do not sufficiently separate between environmentally-extended input-output analysis (EE-IOA) and input-output analysis combined with LCA elements (EIO-LCA). The suggestion is to focus this chapter only on EE-IOA and move the EIO-LCA elements of this chapter to the "Hybrid Approaches". (Giljum)
Accepted with modification, clarification will be done with expert.

No 31.

EIO-LCA is useful for identifying the flows that account for the most significant environmental impacts at the level of study, and serves as a sound basis for mitigation policy. (Schepelmann et al 2008).
In paragraph 2.2.4.1 is stated: "*The EIO-LCA model is a linear model in that it assumes that USD 2 demand has twice the environmental effect of USD 1 demand in the same sector of the economy when in fact scale economies applied in a sector might have the effect of reducing the environmental effects per dollar of demand.*"
The same applies to P-LCA, (and in general to all methods here analysed) as proportionality between FU and emissions is assumed, and therefore, any scale effects in reducing emissions are usually neglected (*ceteris paribus* assumption). (Masoni)
Noted.

No 32.

From the reviewer's perspective it is not justified keeping the method EIO-LCA as a separate method in addition to the Hybrid Approaches in this study. The reviewer therefore suggests focusing on EE-IOA in the input-output chapters of the report and properly evaluating the strengths and weaknesses of EE-IOA in contrast to EIO-LCA/Hybrid Approaches. (Giljum)
Rejected, because given by tender.

2.2.1 Methodological description.

No 33.

In the methodological description, the authors focus on EE-IOA, not on EIO-LCA. The authors use one very specific application of EE-IOA, i.e. an example of energy/emission-related IOA. The first sentence in 2.2.1 reads "... *and then assign emission factors to sectors defined in the IO tables*". The reviewer suggests to make explicit that this is only one possible application of IOA and suggests using "environmental factors" instead of "emission factors", in order to better reflect that IOA can deal with a large number of different environmental factors, covering aspects of materials, energy, water, land, waste and emissions [142-144]. (Giljum)
Accepted, with modification, wording will be changed.

No 34.

The sentence on page 22 "*Overall the EIO-LCA is therefore equivalent to the method usually referred to as basic hybrid approach*" is therefore inappropriate in two ways. First, as it is not connected to what has been written in this chapter above (the chapter above describes EE-IOA, not EIO-LCA). Second, this sentence makes clear that a significant overlap can be observed between EIO-LCA and the "Hybrid

Approaches". This backs the reviewer's suggestion to focus chapter 2.2 only on EE-IOA and include EIO-LCA in the chapter on "Hybrid Approaches". (Giljum)

See above

2.2.2.1: History

No 35.

If the reviewer's suggestion to focus on EE-IOA, a better coverage of the historical development of EE-IOA is required here. (Giljum)

Rejected, just overview.

2.2.4.1 Methodological gaps.

No 36.

Again, the first sentence that EIO-LCA gives average results of economic sectors defined in the IO tables, refers to EE-IOA, not EIO-LCA.

In the second sentence, the authors state that in IOA, imported products are treated the same as domestically produced products. This is only true for a part of existing IO studies. In the past 5 years, a large (and rapidly growing number) of studies applied multi-regional input-output (MRIO) models exactly in order to avoid distortions of results due to the assumption of equal production technologies [see, for example, 145, 146-154]. The authors need to consider recent development in MRIO modelling in this chapter. (Giljum)

Accepted with modification, will be checked with expert.

2.2.4.2 Data gaps

No 37.

The statement that only a few countries have provided IO tables, is wrong. A large number of national statistical offices in industrialised, emerging and developing countries publish IO tables and there exist at least three international sources for internationally harmonised sets of IO tables, which cover a large number of countries: EUROSTAT[5], the OECD[6] and GTAP[7]. A summary of available international sets of IO tables is provided for example in the report by Wiedmann et al. [136].

Also an increasing number of countries publish environmental data in a format compatible to IO tables (so-called physical satellite accounts). The authors should at least mention ongoing European efforts in establishing NAMEA (National Accounting Matrix including Environmental Accounts) tables [see 155]. For many EU countries, NAMEA tables exist regarding air emissions and material flows, and currently EUROSTAT is working on NAMEA tables for energy use and water use. (Giljum)

Accepted with modification

2.2.4.3 Necessary future research.

No 38.

Also the statement that the current literature is of no guidance in regard to the necessary future research, is incorrect. Many of the papers and reports suggested above do contain descriptions on necessary further research. This regards particularly the need to provide IO tables with a higher number of (environmentally-

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[5] See http://epp.eurostat.ec.europa.eu/portal/page/portal/esa95_supply_use_input_tables/data/database
[6] See http://www.oecd.org/document/3/0,3343,en_2649_34445_38071427_1_1_1_1,00.html
[7] See https://www.gtap.agecon.purdue.edu/databases/v7/default.asp

relevant) sectors and the need to reduce the time lag between the date of publication of the IO table and its base years. (Giljum)
See above

2.2.5.1 Ongoing development work.

No 39.

EXIOPOL may not only be understood as current research on IO-based assessments, it is one of the major ongoing EU projects aiming at providing European (and global) IO-based data for environmental assessments. The authors should also cite Tukker et al. [142] for a description of the EXIOPOL project. (Giljum)
Accepted with modification, reference to Tukker will be included.

2.2.5.2 Foreseen development work.

No 40.

A large number of IO-based studies have already been developed an applied for China [see, for example, 156, 157-159]. A number of projects are currently being conducted, which aim at developing an IO model for Europe, including EXIOPOL and FORWAST (see http://forwast.brgm.fr). (Giljum)
Accepted with modification, will be checked with expert.

2.3: Characterisation of Material Flow Analysis

No 41.

Also this chapter needs to be improved from the reviewer's point of view. Without explicitly emphasising it, the authors focus almost the entire chapter on Substance Flow Analysis (SFA), e.g. for the assessment of metal flows. Only at some points, aspects of macro applications of MFA, i.e. economy-wide MFA (EW-MFA), are mentioned (e.g. by citing the 2001 EUROSTAT MFA guide). The authors need to separate more clearly SFA from EW-MFA in their description and need to include more recent developments in EW-MFA.
In the introduction to this chapter, the authors need to refer to recent harmonisation and standardisation of EW-MFA methods, e.g. by the OECD [160, 161] and EUROSTAT [162].
When the authors speak about the incorporation of MFA into government policy frameworks, Japan's material policies need to be mentioned, as Japan is the only industrialised country, which defined short-term goals for reducing resource use and improving resource productivity [see, for example, 163].(Giljum)
See above

No 42.

MFA is not well addressed. No clear differentiation among different types of MFA is present in the discussion. For example, according to Wiedmann et al. (2006), MFA tools vary in relation to scale, types and themes of policy making. Thus, Economy Wide-MFA (EW-MFA) is a MFA method for applications related to the macro layer; NAMEA, eIOA and PIOT can be considered as MFA method at meso layer, while LCI and SFA as MFA tools at micro level.
It is not fully clear the scope of this section. I would recommend focusing the discussion on

Depending on the kind of analysis, the focus of a MFA is either on detoxification (SFA) or dematerialization (EW-MFA) (Schepelmann et al 2008).

Paragraph 2.3.3: All MFA methodologies serve as tools to understand the functioning of the physical basis of societies, the interlinkages of processes and product chains, and the exchange of materials and energy with the environment (Moll et al. 2003). Bringezu and Moriguchi (2002) distinguish between two basic strategies according to the primary interest of the analyst. The first strategy may be characterized as detoxification of the industrial metabolism. This means to reduce the release of hazardous substances to the environment in order to provoke less pollution. Related tools are the substance flow analysis (SFA), the bulk material flows analysis or the life cycle assessment (LCA). The second strategy could be described as dematerialization of the industrial metabolism. Dematerialization means to increase the resource efficiency by decoupling material use and economic growth, i.e. to produce more (or the same) by simultaneously using less primary material input.

Paragraph 2.3.4: MFA is a macro method, it can include information from the meso level (branches) but it does not include detailed information on technologies and production side specific aspects. Therefore it is inadequate for the identification of technological potentials on the meso and micro level. MFA gives an indication of the resource productivity of an overall economy, but it is not suitable for the optimization of single production systems. The identification of specific technological potentials on the macro level is impossible but there is still the risk that decision makers can ignore this limitation of EW-MFA. (Schepelmann et al 2008).

Paragraph 2.3.5: The indicators are pressure indicators; they do not tell anything about specific impacts in terms of changes of the state of environment (neither output nor input related pressures do so) and bulk material flow indicators may not be used to indicate substance specific pressures.

Paragraph 2.3.5.2: Concerning technological potentials for optimization, MFA is limited and micro level analysis are additional needed but, combining MFA with micro level analysis (LCA) is limited by several incompatibilities e.g. system boundaries, allocation rules (Schutz and Ritthoff 2006).

(Masoni)

See above

2.3.1 Methodological Description.

No 43.

Figure 2 relates to an application of SFA and the authors need to explain that more explicitly. Parts of Figure 2 are unreadable and it is unclear, from which source this figure has been taken.

The reviewer would recommend also including a schematic diagram of EW-MFA, as this approach is the basis to evaluate the suitability for macro applications of MFA in chapter 5. Such a schematic figure can for example be found on page 30 in the OECD MFA guide [160].

The authors do not mention at the beginning of the description of SFA on page 27 and 28 that they refer to the specific case of metal flows. Only on page 28 the authors write that "*between the amount of new or recycled metal* ...", where it becomes clear that not a general SFA case is described, but a specific application for metals. The authors do not justify, why they focus on metal flows here. If possible the authors should replace this description by a more general description of SFA.

Also in this chapter, the concept of MIPS (Material Input per Service Unit) needs to be mentioned, as this is another important approach of Material Flow Analysis on the product level [for example, 164, 165].(Giljum)
See above, chapter will be edited.

2.3.2.2: Recent developments
No 44.

All the citations in this chapter on "recent developments" are between 1999 and 2003. They thus do not reflect recent developments in SFA and EW-MFA and need to be updated.(Giljum)
See above, chapter will be edited.

2.3.3 Major applications of MFA.
No 45.

Applications of EW-MFA [for example, chapter 4 in 160] are completely missing here and should be incorporated. (Giljum)
See above, chapter will be edited.

2.3.4: Identified gaps in the method
No 46.

Again, EW-MFA is completely missing. (Giljum)
See above, chapter will be edited.

2.4: Characterisation of Hybrid Approaches
No 47.

"Hybrid" basically means the combination of two otherwise distinct approaches. It is therefore used in many different contexts and care should be exercised when using the term. Preferably, a more precise term should be applied. In the context of LCA and IOA, hybrid is used in at least two meanings: hybrid units, that are the combination of physical and monetary units for different columns and rows in the same table, and hybrid data, that is the combination of process level data and industry level input-output data in the same database (Weidema et al 2009).
On the terminology adopted in the report there is not a consensus. The first method (named Integrated hybrid analysis) is not usually referred as "integrated": indeed it is a simple "adding" of EIO data to cure P-LCA missing data . The second one (named Input-output based hybrid analysis) is a real "integrated" approach. (Masoni)
Noted

No 48.

This chapter in general provides a good overview of hybrid IO-LCA methods. (Giljum)
Noted.

2.4.1:Methodological description
No 49.

Please refer to (Weidema et al 2009) for a comprehensive status of the art and a methodological guidance.
Accepted with modification

2.4.4: Identified gaps in the method

No 50.

he question of reproducibility and comparability of assessment studies is very complex and not limited to this specific method. Even in the case of P-LCA, LCA studies of products based on the same PCR for EPD, often lead to different results because of freedom left to analyst in modelling and because of differences in databases.

Accepted with modification.

2.4.4.1 Methodological gaps

No 51.

Also in this chapter, the authors should at least mention recent advancements in the area of multi-regional IO modelling (see above). (Giljum)

Accepted.

2.4.4.2: Data gaps

No 52.

The statement that IO tables only exist for a small number of countries should also be revised in this chapter (see above). (Giljum)

See above.

2.4.4.3: Necessary future research

No 53.

CALCAS D18 (Weidema et al 2009) identifies some research needs. The research recommendations are divided into three areas: data, methods and experience.

Data

In the short term (3-5 years) improvements in the process databases are required, so that they can be more easily integrated with the supply use data, implying the use of a recognized process and product classification, adding economic and production volume data, and applying mass and monetary balancing consistently to all activity datasets. For the mid term (5-10 years), improvements should focus on data availability from statistical agencies. The primary data on physical flows needs to be improved, and the aggregation level in published data kept at the necessary minimum to protect confidentiality. Linking of physical and monetary data and balancing of physical tables should be performed already at the statistical agencies. Statistical agencies should document their estimation procedures better and report on uncertainty, preferably for each cell in the supply-use tables.

Methods

Concerning methods, although the main principles of IO-based and hybrid LCA appears to be clear, there are still many details to be filled in, especially on the harmonization of the two in a tiered or integrated way. Traditional LCA is based on a steady-state, IOA on a 1 year account, with information on capital formation and depreciation. These two different systems should be reconciled. Likewise, process-based LCA is a global network of activities, whereas IOA is a regionally delimited system excluding households and treating imports and exports in an aggregated way.

Experience

Many IOA (including EIOA) and LCA studies have been performed and published. The hybrid approaches have been demonstrated, in most cases using small stylized examples of 5 products with hypothetical data. Application to real case studies

should be encouraged, in order to demonstrate the added value of integrated LCA, and to discover more practical issue like how to resolve the mismatch in activity and product classifications, how to obtain the links between physical and monetary data, how to include uncertainty analysis and demonstrating the application of consistent allocation procedures. (Masoni)

Will be modified in consistency with other methods.

No 54.

The reviewer is no explicit expert in hybrid approaches, but to state that the current literature does not provide guidance on the priorities for future research seems to be strange. See, for example, Wiedmann et al. [136] and Blanc et al. [140] for a discussion on further development of multi-regional hybrid approaches. Evaluating the information in these and related publications should also provide some input to chapter 2.4.5.2. (Giljum)

See above.

2.4.5.3: Improvement in data basis

No 55.

It would be better to refer to chapter 2.1.5.3 regarding the improvements of LCA data, than copy-paste the paragraph from the P-LCA chapter. (Giljum)

Accepted.

2.5: Characterisation of EMC

No 56.

The authors provide a good description of the basic EMC methodology as introduced in 2005, but they do not seem to be aware of recent developments in further developing EMC. (Giljum)

Noted

2.5.2.2: Recent developments

No 57.

The authors should mention that in an ongoing project for EUROSTAT, EMC is currently being further developed through calculating the material consumption of Europe in terms of so-called Raw Material Equivalents (RMEs; i.e. considering the up-stream material flows related to EU imports and exports) to obtain a DMC_{RME} indicator and then calculating LCA-based impact factors for each of the materials in DMC_{RME}.

The authors should also state that EMC has been suggested for inclusion in a basket of indicators for measuring the negative environmental impacts related to EU resource use [135]. This basket of indicators is currently being further developed by the EEA in cooperation with a group of experts. (Giljum)

Reference will be checked for updates.

2.5.4.1: Methodological gaps

No 58.

DMC was the system boundary for the initial EMC method, currently, EUROSTAT aims to also include the up-stream, indirect material flows through changing to DMC_{RME} as the basis. (Giljum)

Reference will be checked for updates.

2.5.4.2: Data gaps
No 59.

The authors should mention that DMC data are available for all EU-27 countries [see 71]. Already in the original EMC publication, EMC data were calculated for all EU-15 countries[8]. (Giljum)

Reference will be checked for updates.

2.5.4.3: Necessary future research
No 60.

The study by Best et al. [135] includes a chapter on necessary further research for the EMC indicator. (Giljum)

Reference will be checked for updates.

2.5.5.1: Ongoing development work
No 61.

It is wrong that there is no ongoing work on EMC. EUROSTAT is currently working on an improved EMC for the EU (see above). Results from this project will be presented at the end of 2010. The current work by EUROSTAT and the EEA also determines the foreseen development work in the near future (in chapter 2.5.5.2). (Giljum)

Reference will be checked for updates.

2.5.5.3: Improvement in data basis
No 62.

It is not clear, how EMC results would improve, if internal flows were included. What exactly do the authors mean by internal flows? The inter-industry flows represented in an IO table?(Giljum)

3 Evaluation scheme

No 63.

The authors should include a short note, why EMC has been excluded from the 10-years future scenario. EMC is a method, which was only recently introduced and it can therefore be expected that significant improvements will take place in the next 10 years. (Giljum)

Accepted with modifications.

No 64.

There is an overlapping in those criteria: guidelines and text book can coincide, code of practice and standardisation are two steps of the same process. So, a sort of "double counting" is possible.

It should be differentiated the case of public available data (preferable), as for national accounting tables, and confidential data. (Masoni)

Double counting was avoided.

3.1.2 Applicability
No 65.

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[8] See http://www.leidenuniv.nl/cml/ssp/projects/dematerialisation/index.html

I propose not to use this criterion for the reasons indicated below:

It is stated, "The life cycle methods should preferably be applicable as broadly as possible". I don't fully agree with this assumption. In many cases specialised tools are much better than a general purpose tool (Zamagni et al 2009a). This is a value choice that could result in biasing the conclusions.

In particular, on "a broad range of good and services", I do not agree: this criterion could be acceptable for a micro level analysis but it is not relevant in many macro level analyses. If the sustainability question is "how the decoupling is progressing in Italy?" the question refers to the overall economy and not to specific products or services. So this criterion will not be meaningful.

"A broad range of tasks": Again, a set of specialised tools could be preferable to just one general purpose tool.(Masoni)

Rejected, this criterion reflects the need for a consistent application between micro and macro level. It is agreed that specialized methods can be better but then they do not serve the purpose addressed by the tender.

3.1.3 Stakeholder acceptance

No 66.

One could argue that the applications are related to the age of the method. Younger methods are penalised by three sub-criteria.

Sub-criterion *Inclusion of stakeholders*: Any scientific sound method is developed by scientists. Stakeholders shall be part of the needs analysis. In my opinion the question should be posed in different way: is the method allowing for a participatory approach? But how the decision process is organised is often independent from the method used in the assessment.

Sub-criterion of *policy makers' application*. Here there is a confusion between acceptability and level, type of applications. Please refer to my general comment on levels of sustainability decision questions and on my comments on the applicability criterion. (Masoni)

Rejected. Methods have similar age, carbon footprint standard shows opposite.Participatory approach is already covered in aspects.

3.1.4 Objectivity in application

No 67.

In my opinion the *Reproducibility* is depending on:

- data sources
- modeling assumptions /choice
- value choices

I suggest adopting this set of subcriteria.

Assumptions are not only value choices: for example in P-LCA modelling, the practitioner always makes assumptions. Value choices are mainly in the impact assessment phase.(Masoni)

Noted. Data source is covered by different criterion. Value choices are covered as aspect.

3.1.5 Communicability of method

No 68.

I suggest modifying in *Communicability of method and results*. Please note that the simple existence of a communication tool does not imply that it is effective.(Masoni)

3.2.1 Scientific soundness

No 69.

Sub-criteria: I'm not sure *validation* is the right word. I would prefer "verification". I suggest to add a sub-criterion: existence of a physical principle to be used as overall check (conservation of Mass and Energy, for example).
Accuracy is the distance from the true value: in environmental assessment the "true" value is not measurable. All the listed "validation" (better: verification) checks refer more to precision. Existence of a critical review process: Someone could argue the contrary of what stated: if a critical review is required that means that the overall method is not transparent and could be misused.(Masoni)
Noted. Proposal: Validation/Verification

3.3.2 Suitability for time dependent/specific? models

No 70.

The authors should mention that all five selected methods are ex-post methods in their basic conception. The methods need to be linked to other models or modified (e.g. through scenario analysis), in order to reveal potential future impacts.
The authors mention that the targeted time between collection and provision of data should be 12 months. This seems to be an unrealistically short time frame, to which likely none of the methods could ever comply (neither LCA factors nor IO tables are likely to be available within a time frame of one year, as data collection and processing procedures take long in both cases). (Giljum)
Rejected.. Re time lag: for P-LCA data provision is a matter of days.

(A3) Weighting scheme

No 71.

The development and application of the weighting scheme is clearly described and transparent.
However, the authors (or the experts from JRC IES) should include a more extensive description, why exactly those 5 criteria have been selected as knock-out criteria. How have those 5 criteria been identified as critical for the evaluation of the methods? The definition of knock-out criteria have wide-ranging impacts on the overall conclusions of the study (e.g. for micro applications, three of the five methods are kicked out). (Giljum)
Accepted. Knock out criteria will be removed

No 72.

The method is clear in its description and transparent. I personally have some problems with knockout criteria: all the analysed methods have pros and cons, and their usefulness strongly depends on the specific sustainability decision context. I think it is of value to provide conclusions on what are the preferable methods in some specific situation contexts, but they (the situation contexts) should be better and more detailed differentiated. Of course, there are specific situations where one method is not applicable (for example, it does not make any sense applying EW-FMA for a product re-design), but for the purpose of the report, where the decision contexts are not detailed, I recommend not knocking-out any method. (Masoni)

4 Evaluation

No 73.

In the summary tables, the authors only state that some methods are knocked out, without providing information, which specific knock-out criteria the respective methods did not fulfil. It would be important to add this information, e.g. why EIO-LCA, MFA and Hybrid LCA have been knocked out for the "micro level – present" evaluation.
Accepted

No 74.

Given the still existing deficits in current P-LCA data bases (e.g. limited availability of geographically explicit impact factors reflecting differences in impact intensities in different countries and world regions; or limited availability of time series of impact factors), the statement that "*the improvement potential on the micro level is limited for P-LCA*" (p. 10) is surprising. Given the fact that P-LCA has been applied on the macro level only in few studies so far, the statement that the improvement potential of P-LCA on the macro level is also limited is even more surprising. More detailed comments on this issue are provided in the review of chapter 5. (Giljum)
Noted.

No 75.

As mentioned in the section on general observations above, the overall results seem plausible, apart from the fact that P-LCA ranks highest also for macro applications. However, the reviewer suggests to rethink a number of particularscores, in order to achieve higher consistency and to incorporate more recent information in the scoring exercise. These particular issues are discussed in the following. (Giljum)
Noted

No 76.

Please refer to the general comment on decision situation context. I do not understand why at macro level only "monitoring" situation is envisaged. At micro level, in most of the described cases (e.g. product improvement), a simplified method is most appropriate.
Correctness of the application of the evaluation scheme and single criteria to the different life cycle methods
As the criteria are applied on the basis of an expert judgement, there is no "correct" value. In some cases, for example, I would have scored differently.
Consistency and impartiality in assigning scores
I feel a sort of bias as the authors are all working directly with LCA and (in one case) EIO-LCA. For example, I have some perplexities for P-LCA scores on macro applications.
Plausibility of the results
MFA and Hybrid knocked out for macro applications are not plausible results, basing on the number of applications of the two methods available also in policy related situations. (Masoni)
Noted

No 77.

P-LCA, as resulting from the scoring, seems already perfect: this is not plausible, looking at the scientific literature proposing new researches.(Masoni)

Rejected, score is on compliance, not perfection. And there is still a significant difference to top score of above 400

No 78.

P-LCA as a macro method ranks very high, despite a number of deficits. Whereas the overall scoring revealed plausible results, one result, however, is surprising: that P-LCA was valued as the best available method for macro assessments. The authors provide high scores for macro P-LCA, although in the accompanying text, a number of crucial deficits are listed. Some examples: " ... *since the extrapolation of process data [to the macro level] is neither entirely defined nor easily understood*" (p. 67). "*On the macro level, however, consistency and reliability of compiling or up-scaling the data is not satisfactorily addressed*" (p. 80). "*Since process-based data are collected on the micro level, the originally intended level of resolution is consistent with micro level applications, but not with macro level applications*" (p. 83). In the review on chapter 5 below, the reviewer therefore emphasises and discusses inconsistencies between the text accompanying the evaluation and the related scores, which are particularly striking for the valuation of P-LCA assessments on the macro level. The reviewer's view is also supported by statements in existing bottom-up LCA studies on the macro level, such as the study by Jansen and Thollier [166] on product consumption in Belgium, which is also cited prominently in the study. In this paper, Jansen and Thollier state: "*It seems inappropriate to discuss in much detail how the analysis done could be improved and the outcome of a market bottom-up LCA made more robust. This is mainly because the environmental impact of products (EIPRO) project and various other national projects using an approach based on extended input-output analysis (e-IOA) have demonstrated that e-IOA is superior for the purpose of defining the product categories with the highest environmental impacts from consumption*" (p. 51). If the authors of the study cite this paper prominently, they should consider the experiences by those colleagues, which actually applied P-LCA on the macro level, in the scoring. (Giljum)

Noted. Consistency checks will be made.

4.1 Evaluation of the present situation.

4.1.1.1.1: Guidelines or code of conduct

No 79.

P-LCA: The authors state that guidelines can be found on both the micro and the macro level. The reviewer is aware of the ISO processes, however, not of the fact that guidelines exist for the application of P-LCA on the macro level. It would be necessary that the authors provide more information to justify a score of 3 on the macro level. (Giljum)

Rejected, references will be included (e.g. World Steel Sector guidelines, ILCD), procedural guidelines applicable on both levels.

No 80.

EIO-LCA: It is unclear, whether the authors focus on EE-IOA or on EIO-LCA (see chapter 2 above). It is also unclear, how the general LCA guidelines should be

applied also for EIO-LCA. The authors should provide an example, what this means in practice. If this chapter is focused on EE-IOA as suggested by the reviewer, the score should be higher for macro level compared to the micro level. (Giljum)
Procedural guidelines applicable for EIO-LCA.

No 81.
MFA: The authors should mentioned the recent MFA guidelines from OECD and EUROSTAT, which provide an international standardisation of EW-MFA. Given this available standardisation, the reviewer suggests a score of 3 for the macro level. (Giljum)
Accepted with modification, score will be changed to 3 on macro level.

No 82.
Hybrid-LCA: It is not consistent to give a score of 2, if no specific guidelines are existing. (Giljum)
Procedural guidelines applicable for Hybrid LCA.

4.1.1.1.2: Detailed expert documentation
No 83.
It is not clear to the reviewer, why the authors were not able to distinguish between P-LCA and EIO-LCA in publications. In most cases, already the abstract provides a short summary of the applied methodology. (Giljum)
Accepted and adapted.

No 84.
P-LCA: To the reviewer's view, it is not justified to give a score of 4 at the macro level. Only a few studies exist, which applied a bottom-up P-LCA on the macro level. The mentioned study by Jansen and Thollier [166] cannot be regarded as a detailed expert documentation, as the authors explore one option for economy-wide P-LCA and clearly state the limitations (see also below). (Giljum)
Accepted, check references, score will be changed to 2 on macro level.

No 85.
MFA: "*Extensive textbook is available*". To which textbook do the authors refer here? (Giljum)
Reference added.

4.1.1.1.3: Comprehensible calculation and transparency
No 86.
P-LCA: "*There is no defined way to extrapolate process based data to the macro level, therefore the comprehensibility of the calculation may be limited but this is not a methodological issue.*" The reviewer disagrees with this statement. It is a methodological problem that no defined way exists on how to extrapolate process data from the micro to the macro level. For example, Jansen and Thollier in their study on Belgium state that "*In absolute results, the impacts from a bottom-up LCA seem rather underestimated. This can be explained by constraints inherent in LCA methodology (system boundaries), the difficulty of defining and selecting representative base case products, and, probably most important, market and LCA data constraints*" [166, p. 51]. So there are methodological questions involved in the upscaling exercise. A score of 3 therefore seems to high. (Giljum)
Accepted, reduce score to 2.

4.1.1.1.4: Availability of standardisation for method
No 87.

MFA: It is not correct that no standardisation is available for MFA. For EW-MFA international standards exist in term of the OECD and EUROSTAT guidelines (see above). So a score of 3 or even 4 would be justified in this case. On the micro level, there are standards for calculating MIPS [164, 167], which should be reflected in the micro score for MFA. (Giljum)

Rejected, these are guidelines not standards.

4.1.1.3.1: Inclusion of stakeholders
No 88.

MFA: in the development of EW-MFA, the EUROSTAT Task for on MFA played a crucial role. In the task force, experts from EUROSTAT, the EU Commission, national statistical offices and ministries as well as experts were represented. A score of 1 seems therefore too low for the macro application, as there was higher stakeholder involvement than in the case of EMC (which received a score of 3). (Giljum)

Accepted with modification, score changed to 2, because important stakeholders like business and NGO were missing.

4.1.1.3.4: Method application by policy makers
No 89.

P-LCA: The authors state that P-LCA has been widely applied on micro and macro levels. However, apart from the study by Jansen and Thollier, the authors do not provide any examples for macro-level applications. The score of 4 on the macro level needs to be justified by empirical evidence. (Giljum)

References will be added, e.g. German packaging ordinance.

No 90.

EMC: The EMC has been suggested as a core method in a basket of indicators to monitor implementation of the Resource Strategy of DG ENV [135]. The basket is currently further developed by DG ENV and the EEA in order to operationalise it for use in EU policies. A score of 0 is therefore unjustified on the macro level. (Giljum)

Rejected, just proposed.

4.1.1.4.1: Reproducibility
No 91.

EIO-LCA: The authors state that "*the method is fixed*". This is not consistent with what has been written in chapter 2.2.4.3, where the authors state that "*it is necessary to formalise the boundary setting in the methodology*". If not even the system boundaries are clearly defined, a score of 4 seems to be inappropriately high. (Giljum)

Rejected, compared to the other methods it is more fixed, therefore 4 is consistent.

No 92.

EMC: The reproducibility of EMC results critically depends on (a) how the material balances for the different materials are calculated and (b) which database is used for extracting impact factors. As the methodology is currently still under development and is likely to change in various ways until standardisation is agreed, a score of 3 for EMC seems to be too high. (Giljum)

4.1.2.1.1: Existence of Scientific societies

No 93.

EMC: Researchers from the Industrial Ecology and the LCA societies work on EMC; it is highly unlikely that there will ever be a scientific society only focusing on EMC. The score for EMC should therefore by as high as e.g. the score for EIO-LCA, where a similar situation is observed. (Giljum)
Rejected. There are distinct societies for others.

4.1.2.2.2: Method is defined for: system boundary

No 94.

In the current guidelines for EW-MFA by OECD and EUROSTAT, the system boundary for EW-MFA studies is clearly defined and internationally standardised. A score of 4 would therefore be more appropriate for macro applications. (Giljum)
Check, increase to 4 on macro.

4.1.2.2.3: Method is defined for: multifunctional situations

No 95.

MFA: It is incorrect that the focus of MFA is always on single materials. In assessments following the MIPS (Material Input per Service Unit) concept, the allocation issue is important and therefore clear allocation procedures have been defined [see 164, 167]. (Giljum)
Noted, wording is changed.

4.1.3.2.1: Time series

No 96.

P-LCA: The authors state that " ... *most P-LCA data sets only exist for one point in time for one product from one manufacturer, and most data sets are not regularly updated* ...". How can P-LCA than receive a score of 3, if these crucial gaps for time-series applications still exist? (Giljum)
Rejected, if time series is desired, updates are made, as indicated in chapter. Distinguish foreground- background data

No 97.

MFA: Regarding the availability of time series data, EW-MFA should receive the highest score of all methods regarding the macro applications. EW-MFA data exist for all EU-27 countries in a time series from 2000 to 2005 [71] and for the EU-15 back to the year 1970 [168]. (Giljum)
Change to 3.

No 98.

EMC: In contrast to MFA, EMC also uses impact factors, which in general are not available in time series. So the score for EMC must be lower than for MFA. (Giljum)
Rejected, see above.

4.1.4.1.1: coverage of life cycle

No 99.

P-LCA: In Part I of the review it was suggested to base the scoring on the real world situation, not on theoretical options. The authors write that "*there are no theoretical*

limitations in data availability for any life cycle phase. Though in specific applications data may be hard to obtain, this is no methodological issue, at least not on the micro level". In the reviewer's view, the scoring should be based on an assessment, whether or not data are *actually* hard to obtain, and not whether or not there are *theoretical* limitations in data availability. The score of 4 is therefore not sufficiently substantiated. (Giljum)

Rejected, score of 4 is substantiated by methodological aspects.

No 100.

MFA: Not national accounts provide the MFA data, but satellite accounts to the System of National Accounts (SNA) contain these data. On the European level, the NAMEA system (see above) is the common data organisation format. (Giljum)

Accepted, wording changed.

4.1.4.1.4: Publicly accessible inventory databases at affordable cost
No 101.

P-LCA: It is unclear, why the authors list the mentioned data bases as "macro level databases". To the reviewer's knowledge, all the cited databases refer to processes and products and to not contain any economy-wide data. As Jansen and Thollier explain in their bottom-up LCA study on Belgium, inventory data on the macro level need to be compiled from a large number of diverse sources and "*publicly available data for products are a general problem*" [166, p. 48]. Therefore the reviewer suggests to down-scale the score for macro applications to 1, as there are no databases available for inventory data on regions or countries. At the same time, the score for the micro level should be increased to 3, as there are a number of databases (as cited by the authors) for this level. (Giljum)

Rejected, with the macro level applied here these are macro level databases representing average data in sectors, not individual products.

4.1.4.2.2: Independent review
No 102.

P-LCA: The authors state that data review is an essential part of the P-LCA methodology and devote a score of 4 for both micro and macro level. As discussed in the general observations above, the reviewer suggest to describe in more detail, how this review process is organised and implemented in practice, e.g. within the ecoinvent or the ELCB database. Only, if comprehensive review processes are actually installed in practice, a score of 4 would be justified. Simply stating that it is part of the methodology is not enough substance for the highest possible score.

Rejected, reference will be added.

No 103.

EIO-LCA: Apart from the fact that actual review processes in LCA databases might have weaknesses (see above), the authors do not discuss issues related to the review of IO tables, which are the second essential element of the EIO-LCA methodology. This aspect needs to be described in order to evaluate, whether full score is justified here. (Giljum)

Noted, full score is already given.

No 104.

MFA: There are procedures in place, which ensure a review of MFA data. For example in the course of the EUROSTAT process collecting MFA data from national statistical offices, experts at EUROSTAT cross-check data and perform plausibility

checks (e.g. summing up different sub-categories to check totals) in order to guarantee a certain level of data quality. So at least for macro MFA, a score of 0 is not justified. (Giljum)

Accepted, macro score will be changed to 2.

No 105.

EMC: As EMC uses data from macro MFA, a score of 0 also seems not appropriate. (Giljum)

Accepted. See above

No 106.

ybrid LCA: Also here, aspects related to reviews of the IO tables, the second data component of the methodology, need to be addressed. (Giljum)

See above

4.1.4.2.3 Data representativeness

No 107.

P-LCA receives the full score regarding "data representativeness", as "*the P-LCA method can achieve good data representativeness ...*" (p. 84). For the score, the crucial question is, whether P-LCA is achieving a high representativeness in practice, not whether it *can* have a good representativeness. (Giljum)

Rejected.

4.1.4.2.4 Data documentation

No 108.

P-LCA receives full scoring regarding data documentation, as "*data are required to be documented in a transparent way*" (p. 85). Again, the determining point is not, whether the methodology demands full documentation (all methodologies evaluated in this study pose that demand), but whether and how documentation is done in practice. (Giljum)

Rejected. References.

4.2. Evaluation of future potential

4.2.1: Projects considered for the future potential

No 109.

In the area of EE-IOA, the authors should mention the series of six projects recently commissioned by EUROSTAT, which aim at establishing an environmentally-extended multi-regional input-output system for Europe [see 99][9]. These six projects will produce a harmonised system of IO tables (based on the existing EUROSTAT set of IO tables with 60 sectors) for all European countries, linked by bilateral trade data and extended by environmental data, such as air emissions, material flows, energy use and water use. These projects have started at the beginning of 2010 and will end in 2011. (Giljum)

Accepted, projects will be added.

No 110.

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[9] Download from: http://epp.eurostat.ec.europa.eu/portal/page/portal/calls_for_tenders/calls

Another initiative that should be mentioned is the OECD initiative on "Measuring material flows and resource productivity" [169]. OECD environmental ministers passed the second recommendation with the same title in 2008 [170], demanding an intensified application of MFA indicators in OECD policy making. This initiative will likely increase the availability of EW-MFA data also in non-EU countries. (Giljum)
Accepted, projects will be added.

No 111.

The judgement that EMC will not be improved in the next 10 years is not reflecting ongoing processes and activities. EMC has been adopted as part of a basket of indicators to measure the negative environmental impacts related to resource use, which is further developed by DG ENV and EEA. Furthermore, a current project on EMC by EUROSTAT will improve both the material flow data, on which EMC is calculated (moving from DMC towards DMC_{RME}) as well as the impact factors of different types of materials. (Giljum)
Check. See above.

5 Discussion

No 112.

This chapter strongly depends on the previous ones, please refer to those comments.(Masoni)
Noted.

No 113.

Chapter 6 provides a valuable summary of the detailed evaluation for each of the methods.
If the authors take into account (some of) the detailed comments on the scoring provided above, the overall scores would change for some of the methods and this would need to be reflected also in the text of chapter 6.
Noted.

5.1 P-LCA

No 114.

P-LCA: there is an apparent contradiction when is stated that there is room for improvements in data availability, while this point has been scored at maximum. (Masoni)
See above. P-LCA: needs to be checked for consistency concerning scores regarding theoretical and practical application. In any case, there is no contradiction, as availability is already very high, but can always be improved

5.3: MFA

No 115.

Figure 7 should be moved below the heading of chapter 6.3. Otherwise the reader assumes that this figure belongs to the previous chapter.
Accepted

No 116.

MFA: as the final goal of the report is to "contribute to define a sound approach towards the development of the three sets of decoupling indicators, as announced in the EU Thematic Strategy on the Sustainable Use of Natural Resource" knocking out MFA for its low score for environmental impact assessment is not justified. (Masoni)

Accepted. K.o. criteria will be removed.

No 117.

he authors rightly point out that MFA does not include an impact assessment, but has its value in providing the basic physical flow data, to which impact factors can be linked for an impact assessment. Maybe this is one reason, why it is worth considering MFA in studies such as this one, which evaluate the environmental impact assessment potential of different methods.

Noted.

5.5: Hybrid LCA

No 118.

Is it really justified to rate the sub-criterion "Comprehensible calculation and transparency" as a K criterion and thus knocking-out all Hybrid Approaches from the present application due to the low scores in this particular criterion? The reviewer suggests rethinking the categorisation of K criteria. (Giljum)

Hybrid LCA: I do not agree with knocking out the method for the criterion "Comprehensible calculation and transparency". Hybrid LCA is a flexible method, its implementation depends on a case-by-case situation, but normally the adopted approach is well described, with a great attention to the computational structure.(Masoni)

Accepted. K.o. criteria will be removed.

6 Final comparison

No 119.

Based on the results of the previous analysis, the comparison among the methods is clear and objective. There are overlapping and some repetitions with the previous chapter. (Masoni)

Noted.

No 120.

Chapter 7 provides a comparative summary of the evaluations of all five methods for both micro and macro level applications. It is an important chapter, as it provides the basis for deriving recommendations, which of the methods is best suited and ready for application for different purposes of analysis. The chapter is well-structured and reflects/summarises the main results from the scoring exercise.

Noted.

6.1: Micro level applications

No 121.

Some of the arguments already listed in detail in chapter 5 again are valid in this chapter. For example that practically no improvement potential is assigned to P-LCA in the next 10 years, which is surprising, given generally still limited spatial or temporal explicit impact data in currently available data bases.
See above

6.2: Macro level applications

No 122.

As argued above, the reviewer criticises the high scores for P-LCA on the macro level regarding several criteria and suggests rethinking the scoring in particular for this application of the method.(Giljum)
See above

A 6 Waste evaluation

No 123.

The reviewer's knowledge in the particular area of waste management is limited. Therefore, no detailed comments on the scoring in this chapter are provided. The overall results of the method evaluation, i.e. P-LCA being currently the best option for analysing waste-related issues, seem plausible and correct.
Noted

No 124.

The specific goal of the assessment (decision context) is not sufficiently detailed. "*Not all criteria considered in the previous evaluation are relevant for this particular evaluation*": This sentence is in contradiction with the adopted methodology. I understood that the selected criteria should cover the whole spectrum of decision situations, now here I understand that, for a specific case, some of the criteria are not relevant: the same situation can happen for most of the effective situations. The conclusion I learn from this is that we should evaluate the suitability of the methods on a case-by-case approach. (Masoni)
Noted. They are not relevant in the sense that they are not expected to differ from te general evaluation, needs to be reworded.

Applicability of the Life Cycle Methods for waste management

No 125.

The authors state that MFA is exclusively focusing on input flows. This is not correct. For example, in EW-MFA, the establishment of full material balances (including inputs, stock changes and outputs) are always the final objective and the commonly used schemes for EW-MFA (see suggested scheme in OECD publication) prominently include output flows and related output indicators. There are also well-known MFA-based publications, which focus entirely on output flows. The report by the World Resources Institute and other institutions called "The weight of nations. Material outflows from industrial economies" [171] is probably the most prominent

international example for such an output-oriented MFA study. The reviewer suggests that the authors include those aspects of MFA in the evaluation of chapter 8. (Giljum)
Reference will be checked

7 Conclusions and Outlook

No 126.

The authors should include a short paragraph containing their recommendations for further implementation of the methods. The formulation that "the study can contribute to the development of sustainability indicators ..." is quite vague and open. This section of the executive summary could profit from a more explicit statement on which methods should be further developed and implemented by JRC or other national and European institutions and on how the results of the study should be used by JRC in the future development and implementation of the different methods.
Noted, but outside scope

No 127.

The final chapter 9 includes the overall summary and conclusions from the evaluations. Apart from the issues addressed below, the conclusions are robust. However, as a reader, one would be interested to learn more about the processes, to which the results of this study will feed into. How is JRC intending to use the results? How do the results feed into the further elaboration of the European LCA database at JRC? For which particular policy areas does JRC aim to use the results? If the authors could provide a more extensive description of these issues, the outlook part of Chapter 9 would profit.
Noted, but outside scope

No 128.

The authors state that "for micro level applications, only process-based LCA (P-LCA) and Environmentally-Weighted Material Consumption (EMC) are generally suitable at present." It is unclear to the reviewer, why EMC is now being rated as suitable, when the summary of the scoring (pages 108 and 109) do not reveal that. This is an inconsistency which needs to be removed. On page 10 in the executive summary, it becomes clear that this statement is based on the fact that all other three methods are kicked-out due to several reasons. However, to the reviewer's view this should not lead to the conclusion that EMC is a suitable method for current micro-level oriented applications. As the authors rightly point out, EMC was primarily developed for the macro level and so far there no explicit micro-level applications of EMC exist. Furthermore, the methodology is immature and will likely change in the future. For those reasons, the statement that EMC at present is a suitable method for the micro level is not justified.
Accepted, will be reflected in the wording.

No 129.

In chapter 9, the authors include a section on MFA: "*MFA takes up a special position in this study ...*". This paragraph explains the status of MFA in this study, which the reviewer missed in the beginning chapters (see related paragraph in Part I of the

review). The authors should provide such a paragraph both in the executive summary and in the introduction to this study.

Accepted.

No 130.

The authors explain that the evaluation of the methods was carried out only on a theoretical basis. The reviewer assumes that some of the scores would change significantly, if the practical aspects were more prominently taken into account. For example, the article on macro-level P-LCA by Jansen and Thollier (2006) provides a detailed description on the practical problems involved in the implementation of P-LCA on the macro level. (Giljum)

See above.

No 131.

Before deriving definitive conclusions on the applicability of the LC methods here analysed, more research, clearly beyond the scope of the present study, is recommended. In particular:

The specific decision contexts of interest shall be better defined, because the division in micro and macro level is not exhaustive and, in some cases, could be also misleading. The assessment method here developed has a comprehensive and detail list of criteria. Some of them, in my opinion, require a revision, and some weighting procedure as well, in particular on knocking-out criteria, as better described in comments to Chapter 3 and 4.

After these revisions, the methodology could be re-applied by a broader community of scientists and experts, including scientists directly involved in the development of all methods under analysis. The results of CALCAS project are, in any cases, of interest for the stated purposes of this study. (Masoni)

Noted.

European Commission

Abstract
The European Commission (EC) has strengthened environmental and sustainability oriented policies and strategies by introducing Life Cycle Thinking. Amongst others, this is a key consideration in the Integrated Product Policy Communication, the two Thematic Strategies on the Sustainable Use of Natural Resources and on the Prevention and Recycling of Waste, as well as in the Sustainable Consumption and Production (SCP)/Sustainable Industry Policy (SIP) Action Plan. Reliable and scientifically robust life cycle methods are required to support the implementation, monitoring and assessment needs of these strategies and associated policies.
This project analysed different life-cycle methods and provides an evaluation of their current suitability for assessing environmental impacts in micro level and macro level situations. Some of the methods analysed are interchangeable, while others are complementary. This will depend on the situation in which they are applied and their scope. Where methods are not interchangeable, based on their scope and the scope of the application being addressed, the most appropriate method, or methods, will still need to be used – irrespective of the current/future limitations.
In general, Process-based Life Cycle Assessment (P-LCA), Sector-based Economic Input-Output LCA (EIO-LCA), and Hybrid-LCA will be interchangeable in many applications, while Material flow analysis (MFA) and Environmentally weighted material consumption (EMC) will usually have a different scope. For assessing specific products or product groups, micro applications, generally P-LCA or Hybrid-LCA will be the most applicable methods depending on the scope of the application. For macro applications, use of all interchangeable methods is recommended, due to existing limitations and pending further detailed, independent insights on the methodological strengths/weaknesses.

The mission of the JRC is to provide customer-driven scientific and technical support for the conception, development, implementation and monitoring of EU policies. As a service of the European Commission, the JRC functions as a reference centre of science and technology for the Union. Close to the policy-making process, it serves the common interest of the Member States, while being independent of special interests, whether private or national.

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