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Revision 1 after the open consultation

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D20 Blue Paper on
Life Cycle Sustainability Analysis

Revision 1 after the open consultation

Deliverable 20 of Work Package 7 of the CALCAS project

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Contents

CALCAS is the EU 6th Framework Co-ordination Action with the objective of defining research lines and proposals of networking for innovation in Life-Cycle Analysis for Sustainability.

This Blue Paper consists of two parts:

I) a description of a framework and a road map for a Life Cycle Sustainability Analysis (LCSA) including the ISO standard LCA and providing the overall logic structure and the indications able to combine and integrate different knowledge domains, models and tools;
II) a synthesis of analyses performed in CALCAS related to ISO LCA and other assessment models and a first preliminary indication of research needs.

The Blue paper is addressed to the scientific community for an open consultation to receive specific technical-scientific comments on the LCSA framework and on the research needs identified. Suggestions about the research lines to be developed are also warmly solicited.

A list of specific questions, to make the comments collection and analysis easier, is provided in Annex 3.

This version 1 of the document differs from version 0 distributed for the open consultation as it incorporates specific changes (section 2.1.4 and appendix 2) and minor corrections suggested in the comments. The main outcomes of the consultation are summarised and shortly discussed in Appendix 4.

The list of priorities and research needs identified during the consultation have been taken into consideration in drawing up the final deliverable D22 "*Definition of research lines and exemplary research programmes for Life Cycle Sustainability Analysis, incorporation in EU, national research programmes and academic curricula*".

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ENEA was in charge of general editing and of Sections: 1, 2.6, 4, Annex 1, Annex 4.
CML has written Section 2, 2.1, 2.2, 2.3, 2.4, 2.5, 3.3, Annex 2 and contributed to Section 3.1.
IVL has written Section 3.

Executive summary

The present Blue Paper is one of the key deliverables of the CALCAS project that addresses the question of defining research lines and networking for the sustainability analysis based on a life cycle approach.
Life Cycle Assessment, as standardised by ISO, is well recognised as the most suitable method for the environmental analysis of products. Nevertheless, the question of sustainability assessment, in particular of complex systems with extended and durable effects on the whole of society, requires a broadened scope of analysis and a deepening of modelling.
This Blue Paper presents a synthesis of the main scientific elaborations of the CALCAS on Life Cycle Sustainability Analysis, with illustrative examples, and a first inventory of related knowledge gaps and research needs.

Background: CALCAS project
CALCAS is the EU 6th Framework **C**o-ordination **A**ction for innovation in **L**ife-**C**ycle **A**nalysis for **S**ustainability aimed at identifying research lines on how to increase the efficacy of sustainability decision making, going beyond the shortcomings and limitations of current Life Cycle Assessment (LCA). Its general objective is to further develop the ISO-LCA into a broader scientific framework, named Life Cycle Sustainability Analysis (LCSA) with the following features:

- improved reliability and usability of ISO-LCA;
- "deepening" of the present model (i.e. adding more mechanisms and/or more sophistications) to improve its applicability in different contexts while increasing its reliability and usability;
- "broadening" the LCA scope by better incorporating sustainability aspects and linking to neighbouring models, to improve their significance;
- "leaping forward" by a revision/enrichment of foundations, through the crossing with other disciplines for sustainability evaluation.

Key issues
A comprehensive analysis of the users' needs of sustainability assessment has identified three main applications areas, with specific characteristics and needs expressed by the stakeholders:

- micro or **product-oriented systems**, with limited modifications/effects on space, market, time etc. Their main characteristics are: low variability; low complexity; small uncertainty; good knowledge of data and models. Main expressed needs: standardisation; simplicity; user friendliness; etc.
- **meso systems**, with relevant effects on other systems and on time and space. Their main characteristics are: low variability; high complexity; average uncertainty; availability of enough reliable models and data; main needs: reliability; prevalence of analytical methods over procedural methods or quantitative vs. qualitative; involvement of stakeholders; rebound effects; sensitivity analysis; etc.
- macro or **economy-wide systems**, with low reversibility, high penetration and diffusion capacity in all domains and with relevant effects on all levels. They are characterised by: high variability; high complexity; high uncertainty; many lacks of knowledge and data; main needs: completeness – all possibilities, interactions and mechanisms considered – involvement of experts; combination of procedural and analytical methods; heuristic approach by improvement of learning systems; "upgrading" system; etc.

The analysis from the supply side of the status and trends in assessment methods and the further elaboration of CALCAS have led to a proposal of a system approach for Life Cycle Sustainability Analysis (LCSA) as general framework that can include the three different application areas.

In the original CALCAS proposal New LCA was used as the term to indicate all developments in LCA that go beyond the boundaries of LCA as defined in the ISO 14040:2006 (E) and ISO 14044:2006 (E) Standards (abbreviated to ISO-LCA). The term "New LCA" was changed into Life Cycle Sustainability Analysis in the course of the CALCAS project, as this better indicated the contents of the developments and as the 'shelf life' of the term 'new LCA' was considered to be restricted.
Within the CALCAS project we needed a reference for determining where LCSA starts. The published ISO standards, i.e. ISO 14040:2006 (E) and ISO 14044:2006 (E), constituted the most obvious reference for this. By ISO-LCA we thus mean the written text of these two standards. It is explicitly not our intention to classify the ISO standards as static documents that will not be adapted anymore in future. On the contrary, we hope of course that they will be adapted particularly when some of the CALCAS research topics have matured and become daily LCA-practice. Moreover, issues for new LCA may already have been discussed in ISO TCs and there may very good reasons not to adopt these issues within ISO for other reasons. LCSA is not in contradiction with ISO-LCA, but it builds on ISO-LCA extending its current boundaries to LCSA.

This systems approach is based on the distinction of elements (e.g. activities or unit process in ISO-terms), and on the connection among them by mechanisms. Several types of mechanisms can be distinguished:
- technological relations;
- environmental mechanisms;
- physical relations;
- economic relations;
- social, cultural and political relations;
- normative analysis as to sustainability.

ISO-LCA typically takes into account technological relations only for the inventory analysis, and environmental mechanisms for the characterization. ISO-LCA is left, and thus LCSA starts, when we go beyond one or more of its characteristics. Going beyond can be done in several directions:
- Deepening:
    - going beyond the focus on technological, environmental mechanisms and also including other mechanisms such as physical, social, economic, cultural, institutional and political mechanisms. In this direction the analysis may go beyond the ISO-LCA limitation "focus on the technology and environmental mechanisms" ('*deepening of the scope of mechanisms*');
    - going beyond the focus on currently adopted models reflecting aspects within these mechanisms, e.g., adopting spatially differentiated models. In this direction the analysis may go beyond the ISO-LCA limitations "potential environmental impacts" and "integration of environmental data over space and time" ('*deepening of a particular mechanism*').
- Broadening:
    - going beyond the focus on environmental aspects and also including economic and social aspects in the analysis of a system. In this direction the analysis may go beyond the ISO-LCA limitations "environmental focus only" ('*broadening the scope of indicators*');
    - going beyond the focus on individual product systems and taking sectors, baskets of commodities, markets, or whole economies, countries or the world as starting point of a life cycle analysis approach. From lower to higher level, we may go from product LCA, to meso LCA and eventually to economy-wide LCA for countries, for the EU, for the OECD, for the Association of Southeast Asian Nations (ASEAN) etc. and eventually the world. In this direction the analysis may go beyond the ISO-LCA limitations "functional unit based" and "focus on a single product system" ('*broadening the object of analysis*').

CALCAS is proposing a single unitary framework for LCSA, as "logical" structure able to incorporate knowledge from all domains relevant to sustainable development and to identify a coherent way to link micro analysis (where it is possible to implement a very detailed model, as ISO LCA does) to the macro level where, indeed, most questions of sustainability reside. It is very helpful on one hand to reduce complexity and on the other to clarify the simplification choices which have to be made in the integrative analysis. The new framework, compared to the ISO one, includes few but significant differences, in particular with the merging of inventory and impact assessment steps in just one modelling step.

The framework has been further elaborated in a road map that includes the three major applications area (product level, meso level and economy wide technosystems) identified after the user needs analysis, with some grey zones going from one level to the next. The road map also reflects the possibilities for *broadening* the analysis.

An analysis of a give technological system can be made deeper and less deep, including all or just a selection of domains of empirical knowledge and using different methods and models available for each of these domains.

The LCSA framework defines the procedure in three steps (goal and scope definition, modelling, interpretation) as it has to be described in the report of the specific assessment study; but, as well known, a LCA study is based on an iterative process, specifically in the most complex cases. Moreover, the combination/integration of different knowledge domains and models, as required in LCSA, must be based on detailed analysis of equivalence, consistency, coherence, comparability across different scales of time and space, with related problems of data flow etc. For that, it could be useful to also exploit a working method which can help to work with the LCSA road map, i.e. framing the question, selecting appropriate methods, models, and applying them. This working method gives some suggestions on how to manage the fundamental phase of the integration of the models inside the LCSA road map by an iterative process and consists of three phases:

- a “semantic” analysis, i.e. framing the question and decisions at stake;
- a “syntactic” analysis, in which the available methods and models are identified and selected, taking into consideration data availability and reliability, modelling gaps and strategies to bridge them, identification of the control systems;
- an “operational” analysis, i.e. application of selected models and verification of the numeric results.

Three cases on biofuels, waste management and diet changes provide partial examples of LCSA applications.

The second part of the Blue Paper lists an inventory of knowledge gaps and research needs, derived by the deep analyses performed in CALCAS.

The review on LCA applications, together with other sources explored in CALCAS, has been performed taking into consideration the following main aspects:

- Developments towards deepening, i.e. new approaches which add sophistication to the modelling (e.g. time introduction) and/or try to deepen the present mechanisms or to add more mechanisms than the environmental and technological ones, typically accounted for in ISO-LCA. Regarding the latter, the review highlighted several attempts which contribute to explore the modelling of (micro) economic mechanisms: rebound effects, partial equilibrium modelling, experience curves and the consequential approach are those analysed by this review.
- Developments towards broadening, i.e. going beyond the focus on environmental aspects and/or beyond the focus on individual product systems. Examples of methodological advances are represented by the Life Cycle Costing and Social Life Cycle Assessment, which allow covering the economic and social pillars of sustainability evaluations at product level. On the other side, the development of the hybrid approaches opens up new opportunities for moving the analysis from the product-level: indeed, even if it is considered a complex method, which adds to the cost of already expensive and time-consuming full process LCA, it is considered one of the best choices for the future.
- Progresses in ISO-LCA, with reference to the main methodological aspects on which the LCA community debates from long time: system boundary and allocation. The review pointed out that,

even if the debate will never end, more efforts should be spent on the procedural side, developing and agreeing upon a text that is clear and flexible enough to give adequate guidance on these topics in LCA, in order to increase the robustness and transparency of applications.
- Cross issues, i.e. data quality assessment, simplified LCA, uncertainty and practicability. No progresses in developments have been identified by the end of '90s: several applications exist, but based on the methodological developments of those years.

The inventory pointed out that these methodological advances are characterised by a growing "contamination" with other disciplines closed to life cycle analysis. The SWOT analysis performed on about 30 methods and models mainly served for this purpose: it allowed the identification of opportunities for combinations and/or integrations, towards a deepened and broadened life cycle analysis. Clearly each of these models has its own path of development and its research needs, which have been briefly described: the challenge is to understand how all these advances can make available the necessary knowledge for making the framework operational, i.e. how they can be fit in the framework in a way they complement each other and provide coherent, relevant, reliable and complete output.

The inventory is propaedeutic to the definition of research lines and exemplary research programs that will be the subject of a later document, which will also implement the received comments.

PART I

1 Introduction

Life Cycle Assessment (LCA), as standardised by ISO 14040 series, is generally considered the best available method for the assessment and comparison of potential environmental impacts of products. It is increasingly used by business, public authorities, researchers and non-governative organisations in support of their decision making.
The International Reference Life Cycle Data System (ILCD, http://lca.jrc.ec.europa.eu/lcainfohub/index.vm), led by the European Commission, Joint Research Centre, and the UNEP-SETAC Life Cycle Initiatives (http://lcinitiative.unep.fr/) are the two major ongoing international initiatives for the further development of LCA, in particular addressing the questions of consistency, quality assurance, capacity building and extension to Social Life Cycle Assessment.

So, why CALCAS and this document?

There is an increasing need to assess the "sustainability" of systems and technologies that can have large effects on the overall economy and society, and presently there is no comprehensive approach for doing that. This type of problem cannot be addressed by the present ISO LCA alone as it requires two major advancements:

1. broadening the scope of the analysis from environmental only to the full sustainability scope
2. broadening the scope of the objects of the study, from product level (with the incremental approach of the functional unit) to sector or even economy wide level.

CALCAS is an EU 6th Framework Co-ordination Action for innovation in Life-Cycle Analysis for Sustainability[1]. The aim of CALCAS is to structure the array of LCA approaches that have emerged during the last two decades. Besides LCA as defined in the ISO-14040 (Anonymous, 2006a; Anonymous, 2006b) Series of Standards (abbreviated to "ISO-LCA"; see text box), various other LCA approaches have emerged taking into account more types of externalities (economic and social costs) and more mechanisms (rebound, behaviour, price effects), handling of time ((quasi-)dynamic, steady-state), handling of space (spatially differentiated or spatially independent) and/or meeting specific user needs such as in simplified LCA. CALCAS will thus go beyond the boundaries of ISO-LCA. Going beyond ISO-LCA (see Figure 1), was in the CALCAS proposal referred to as (new) LCA and is referred to as Life Cycle Sustainability Analysis (LCSA).

In the original CALCAS proposal New LCA was used as the term to indicate all developments in LCA that go beyond the boundaries of LCA as defined in the ISO 14040:2006 (E) and ISO 14044:2006 (E) Standards (abbreviated to ISO-LCA). The term "New LCA" was changed into Life Cycle Sustainability Analysis in the course of the CALCAS project, as this better indicated the contents of the developments and as the 'shelf life' of the term 'new LCA' was considered to be restricted.
Within the CALCAS project we needed a reference for determining where LCSA starts. The published ISO standards, i.e. ISO 14040:2006 (E) and ISO 14044:2006 (E), constituted the most obvious reference for this. By ISO-LCA we thus mean the written text of these two standards. It is explicitly not our intention to classify the ISO standards as static documents that will not be adapted anymore in future. On the contrary, we hope of course that they will be adapted particularly when some of the CALCAS research topics have matured and become daily LCA-practice. Moreover, issues for new LCA may already have been discussed in ISO TCs and there may very good reasons not to adopt these issues within ISO for other reasons. LCSA is not in contradiction with ISO-LCA, but it builds on ISO-LCA extending its current boundaries to LCSA.

[1] See Annex 1 for a short description and www.calcasproject.net or http://www.estis.net/sites/calcas/ for deliverables and further information

Of course, several other approaches to sustainability assessment could be chosen, but the advantages of a life cycle approach are apparent and well known. Furthermore, our choice was to build on ISO-LCA, trying to not deviate too much from its present framework but introducing the necessary deepening in modelling (in terms of more mechanisms and more sophistications), required by the above mentioned broadening of the scope.
The theme of sustainability and of its assessment escapes, for its nature, from any simplification, and has controversial social and scientific interpretations. In practice, the request of applications of sustainability assessment at broader and differentiated spectrum of issues has produced a continuous growth of methodological formulations and solutions, and, for those adopting a life cycle approach, going well beyond the ISO standard.
The Biofuel case is, to some extent, emblematic of this situation and of the difficulties, or even mistakes we can incur applying partial or separate assessment systems and provides a strong motivation for a project as CALCAS.

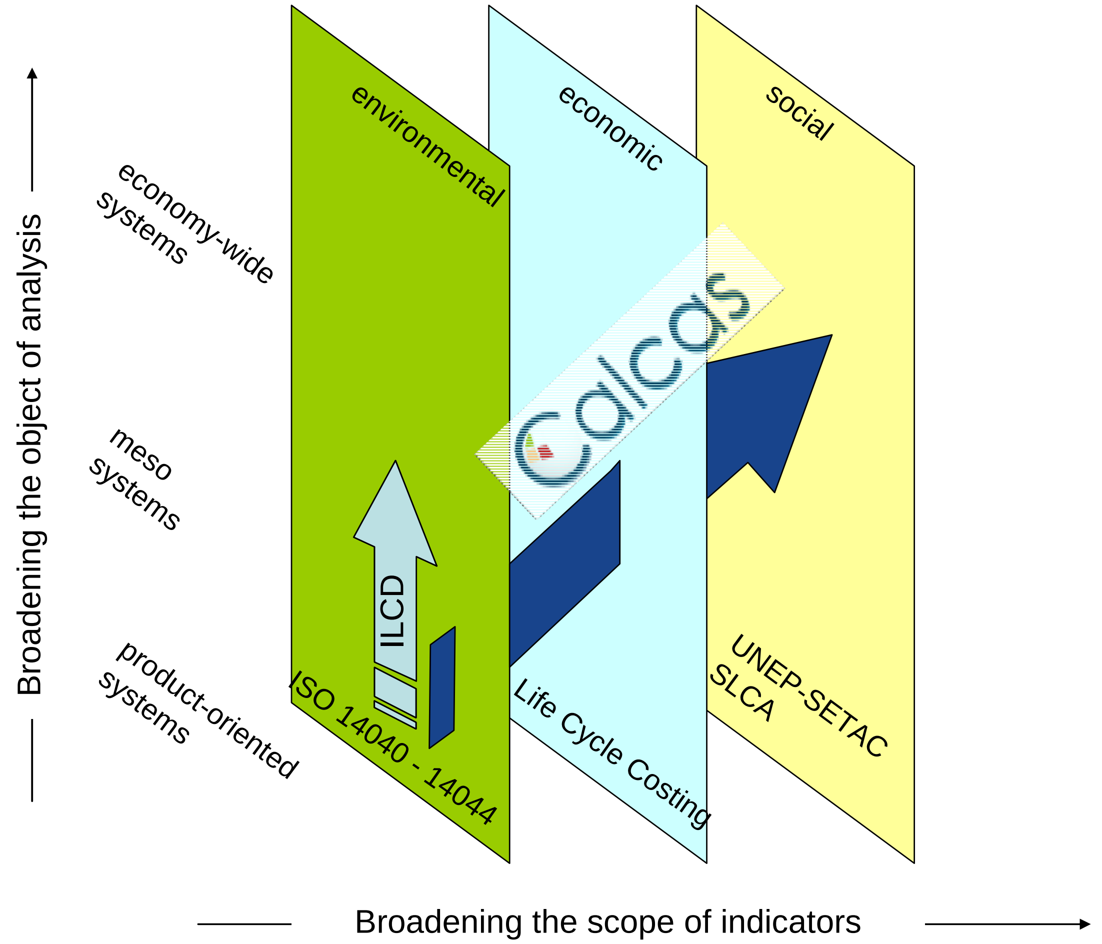

Figure 1: CALCAS: broadening the scope of the analysis from environmental only to the full sustainability and broadening the object of the study, from product level to sector or even economy wide level.

Shortcomings in current discourse: biofuels example
Current policies on biofuels in US and EU have been supported by LCA-type of technology oriented analysis. The effects on global food prices and the induced clearing of rain forests, for example, have not been included in the impact analyses which have been made, missing major social, economic and environmental consequences, as on tropical forest clearing. Partial analysis of such mechanisms now becomes available, but is not integrated in one common framework, making the discussions of the subject disconnected and often unrealistic. Reality, of course, is malleable, but only to a certain extent. This not only holds for physical reality but also for social reality. For example: Requiring a certified statement on the sustainability of biomass, as the Netherlands and EU are doing, may work to some extent at a micro level but not at the macro level of society. The negative effects induced do not reside at the micro level of specific biomass production to which the certification may rightly refer. The negative effects are at the global level of overall food and materials production and consumption, within the constraints of land and water availability, and within the context of fast economic growth in China and India. Getting to the total views is one main aim of the analysis, embedding the micro level analysis in its macro context where many ethical issues reside, like on distributional justice, views on growth (see the *degrowth* discussion), and on strong and weak sustainability.
The same deficiencies in analysis will by necessity be present in any just technological type of analysis. For supporting the evaluation of specific technological developments, we need a broader framework for analysis, incorporating technological, physical and environmental knowledge and broader economic and societal mechanisms, and ethical issues, all increasingly international in nature.

In this regard, CALCAS project has analysed in depth the needs of a demand for sustainability assessment that is very differentiated in terms of questions to be answered and, moreover, in terms of goals, due to the different nature of stakeholders and decisions to be supported. The analysis has been performed assuming two concurrent view points: the perspective of single subjects, classified in four principal categories (business, public authorities, NGOs and consumers, R&D), and the collective perspective of governance systems, also related to different institutional forms (Rydberg et al., 2008).
As result of the analysis, three main applications areas, with specific characteristics and needs expressed by the stakeholders, have been defined[2]:

- micro or **product-oriented systems**, with limited modifications/effects on space, market, time etc. Their main characteristics are: low variability; low complexity; small uncertainty; good knowledge of data and models. Main expressed needs: standardisation; simplicity; user friendliness; etc.
- **meso systems**, with relevant effects on other systems and on time and space. Their main characteristics are: low variability; high complexity; average uncertainty; availability of enough reliable models and data; main needs: reliability; prevalence of analytical methods over procedural methods or quantitative vs. qualitative; involvement of stakeholders; rebound effects; sensitivity analysis; etc.
- macro or **economy-wide systems**, with low reversibility, high penetration and diffusion capacity in all domains and with relevant effects on all levels. They are characterised by: high variability; high complexity; high uncertainty; many lacks of knowledge and data; main needs: completeness – all possibilities, interactions and mechanisms considered – involvement of experts; combination of procedural and analytical methods; heuristic approach by improvement of learning systems; "upgrading" system; etc.

For each of these application areas, different methods and models (or their combination) can be identified as appropriate; indeed, a "one-size-fits-all" solution is not practicable[3] and in CALCAS we analysed them for the three levels. For example, ISO LCA (attributional and consequential modelling),

[2] Many other classifications, not based on the needs analysis, could be proposed, see for example that proposed by the ILCD Handbook (Hauschild et al., 2009). The important thing to be stressed is that the large differentiation of applications cannot be approached with a single method and model.
[3] A similar approach is proposed in Hauschild et al. (2009), in which different modeling approaches are analysed for 4 proposed decision situations.

Life Cycle Costing and hybrid approaches combining IOA and LCA are presently applied[4,5], in the first two application areas, product and meso levels. But for the third level, economy-wide, the question is much more difficult. The very complex relations, mechanisms and trade-off of technology with environment, economy and society can be modelled in many ways, and the combination of all models makes very difficult a reasoned choice. As Huppes and Ishikava (2009) have pointed out,"by selectively picking particular mechanisms and modelling relations we can create any outcome we like"[6]. For this reason "we have to create an integration framework on one hand to reduce complexity and on the other to clarify the simplification choices which have been made in the integrative analysis. The framework must be used in such a way that its structure is able to incorporate knowledge from all domains relevant to sustainable development, using a more or less specified value system" (Huppes and Ishikava, 2009).
CALCAS has developed the framework as a unitary logical structure for the life-cycle sustainability analysis (LCSA) and it includes the three different applications area described above with some grey zones going from one level to the next. A single unitary framework is therefore very helpful, also to identify a coherent way to link micro analysis (where it is possible to implement a very detailed model, using the ISO LCA) to the macro level where, indeed, the question of sustainability resides. In that structure, the most complex level, economy-wide, intends in particular to meet the Public authorities need of having available assessment tools capable of offering more robust support to policy, technological and structural choices, which are, for their nature, often not reversible and have long term effects[7], taking into account that some experiences in that field in the recent past have not been always positive and source of many critics to LCA.
Specific assessment methods and models (and related tools) for some type and level of problems are already available, as for example ISO-LCA and Life Cycle Costing at product level, but the principal knots consist in:

- the completeness of the analysis
- the coherent dialogue among the different models;
- the identification of modes and paths allowing the best compromise among reduction of the variability, reduction of complexity and multidimensionality of the involved parameters, and control of related uncertainties.

One of the CALCAS challenge, surely the most controversial and ambitious, has been facing this "knots", inside the overall and unified setting of the LCSA, how to identify methods and paths to build the needed whole vision of sustainability, without loosing, on the other hands, the analytical and system approach, typical of LCA, in other words, how to combine the telescope and the microscope vision[8].

The framework as unitary logical "structure", its detailed elaboration in a road map and the research needs identified are the core of this Blue Paper.

The Blue Paper consists of two parts plus four annexes. In Part I, Section 2 describes the LCSA framework and road map; Section 3 gives a conceptual example of LCSA application and three

[4] The EIPRO project is an example
[5] The analysis for those two levels still requires some research and development work, as the ILCD and UNEP-SETAC LCI are doing, and CALCAS has also given its contribution in that sense (see annex 1 for a list of project deliverables).
[6] This is not only a theoretical question: the possibility of pre-determining the results we want is presently the strongest objection to the application of LCA in supporting policy and strategy decisions.
[7] Similar needs characterise certainly R&D organisations, but in many cases also private organisations require the assessment of complex systems effects in a long time and wide space perspective.
[8] As pointed out by the Post Normal Science, it is always necessary to take into account that an element, when enters in relation with a larger system, can change its characteristics.

examples of application cases. In Part II, Section 4 makes an inventory of present knowledge and data gaps as regards LCSA models.

2 Road map for life-cycle sustainability analysis

Throughout the CALCAS project, various terms, definitions and classifications of LCA have been proposed in order to structure the discussion on the variety of LCA approaches that have been developed over the past decades. Deliverable 15 (D15; Heijungs et al., 2009) of the CALCAS project has drafted the most important proposals including a structure for deepening LCA based on models from different knowledge domains and a (procedural) framework for new LCA.

Whereas the structure for deepening LCA focuses at distinguishing empirical knowledge (the "facts") from normative positions (the "values") and transdisciplinary integration, and the framework designs the procedural phases of new LCA, additional guidance is needed on how to frame and link questions for sustainability decision support to the most appropriate life-cycle methods and models. As will be shown later, this additional guidance can be supplied by elaborating the procedural framework for new LCA in more detail. In this way, a coherent set of structures is developed that together form the basis for new LCA and for identifying and classifying research issues, lines and exemplary programmes. The procedural framework for new LCA, the elaboration of that framework as developed in this Chapter and the structure for deepening LCA together constitute a general – three dimensional - structure for new LCA linking questions for sustainability decision support to the most appropriate life-cycle methods and models.

We may call this a *road map for life-cycle sustainability analysis (LCSA)*, a term firstly proposed by Klöpffer & Renner (2008; see also Klöpffer, 2008). Their definition of LCSA primarily focused on broadening ISO-LCA to also include economic and social aspects and the 'A' in LCSA referred to 'Assessment'. In CALCAS the focus is on broadening and deepening and the 'A' no longer refers to 'Assessment' but to 'Analysis'[9] (Heijungs et al., 2009, section 3.2). Finally, note that LCSA refers only to *life-cycle* sustainability analyses and not to all forms of sustainability analyses. Below, we will first summarize the main findings of D15 (Heijungs et al., 2009), define what the main limiting characteristics of ISO-LCA are in order to determine where new LCA[10] or LCSA starts and then propose and discuss a road map for LCSA.

2.1 *Summary of findings from CALCAS Deliverable 15 (D15)*

In this section, we summarize the results of CALCAS D15 (Heijungs et al., 2009) in order to enable a better understanding of the discussions in the next sections without having to read D15 first.

2.1.1 The three dimensions of sustainability

The definition of Sustainable Development (SD) establishes clear links with many issues of concern: poverty, equity, environmental quality, safety, population control, and so on. In general, the field of SD is subdivided into three areas: economic, environmental, and social. These so-called pillars or dimensions of sustainability (People-Planet-Profit, People-Planet-Prosperity, PPP, or P3) need to be addressed in assessing the sustainability of a project, policy, etc. Thus, the narrow interpretation in which sustainability and SD is restricted to the ecological pillar alone, is replaced by the wider interpretation where all three pillars are covered.

9 The abbreviation, however, remains the same: LCSA.

10 From here on, we will use the term LCSA instead of 'new LCA' as the 'shelf life' of the term 'new LCA' is restricted.

2.1.2 Modelling mechanisms

In D15, a systems approach was described as distinguishing elements (e.g. activities or unit process in ISO-terms), and connecting these elements by mechanisms. Within the context of LCA, the first type of mechanism distinguished is a causal relationship that connects the level of two activities. The term level refers to the size or intensity of the activity. Some main types of such causal mechanisms were exemplified by the activity of "watching TV":

- There are technological relationships: using a TV requires the existence and hence the production of a TV, electricity, and TV broadcasts.
- There are behavioural relationships: using a TV may induce you to use a sofa, to eat popcorn, and to buy advertised articles.
- There are economic relationships: using a TV implies spending less on other activities.
- There are legislative relationships: TVs are required by certain laws to possess certain safety measures, such as flame retardants and electric fuses.

The second type of mechanism that can be distinguished concerns causal relationships connecting an activity with one or more aspects of a domain of concern, such as an environmental aspect or an economical or social aspect. These mechanisms don't connect the levels of (human) activities, but embody the propagation of consequences from step to step in the domain considered. For example, LCIA follows the environmental mechanism, that starts with emission, and that proceeds through a number of steps (such as increase of CO_2 concentration, change of radiative forcing, temperature change, sea level rise, loss of productive land, loss of agriculture yield, famine, mortality) to a target variable, such as human health. Like for the mechanisms that connect the levels of activities, these are causal links.

Both types of mechanisms represent a chain. However, the chains are of a different nature. The first chain represents the life cycle of the system, while the second chain the impact chain. In the language of ISO-LCA, the first chain represents the inventory analysis, while the second chain represents the impact assessment. The boundary between these two is, however, not so clear as ISO-LCA suggests. Due to the societal response, impacts affect activity levels, and thus the impact chain becomes connected to the life cycle chain. The strict separation between LCI, focussing on the chain of activities, and LCIA, focussing on the chain of impacts, can thus not be maintained in LCSA.

2.1.3 A catalogue of mechanisms and models thereof

Huppes and Ishikawa (2007) abandoned the distinction between LCI and LCIA. They distinguished several types[11] of mechanisms, some of which are part of ISO-LCA, and some of which could be part of a deeper analysis, i.e., of LCSA. The types of mechanisms distinguished by Huppes and Ishikawa are:

- technological relations;
- environmental mechanisms;
- physical relations;
- economic relations;
- social, cultural and political relations;
- normative analysis as to sustainability.

ISO-LCA typically takes into account technological relations only for the inventory analysis, and environmental mechanisms for the characterization. There is, however, a long tradition of including more mechanisms into LCA. For instance, the substitution method for co-product allocation is based on

[11] Huppes and Ishikawa distinguished seven types of mechanisms including micro-economic and meso/macro-economic relations. Here, we have grouped these into one category of "economic relations" since the distinction between micro-, meso- and macro is not clear-cut and commonly adopted and is not necessary for the major structure of this section.

the idea that some economic activities will shrink their activity level when their product is replaced by the co-product. The integration of these other mechanisms is an important way of deepening LCA. Broadening LCA can take place at each of the indicated places, by adding economic impacts, social impacts, or environmental impacts that are not covered by present-day LCA.

Figure 2 illustrates the variety of domains of knowledge and models that can address these mechanisms for deepening LCA. It separates the empirical knowledge (the "facts") from the normative positions (the "values") and the transdisciplinary integration (LCA, integrated models, etc.). The normative analysis is of an entirely different nature, as it is not about empirical knowledge of what is, but about normative positions of what ought to be.

The transdisciplinary integration is in fact the most challenging part of integrated models, such as LCA. It is the art of combining factual knowledge of economic, environmental, social and other aspects with one another, and integrating them with the ethical positions and societal values on economic, environmental, social and other aspects.

Below, the role and possible content of the different elements in Figure 2 is discussed briefly in the form of the models that can address such mechanisms; for a more elaborate discussion, see D15 (Heijungs et al., 2009).

Technical models describe the principal causal relationships that connect the level of two economic activities. In ISO-LCA, technological relations form the central element of the inventory analysis. An LCA of TVs would cover the production, use and waste phase. Not all aspects of these are treated equally, however. Most LCAs of a TV would exclude (or ignore) the broadcast issue and the infrastructure of the electric equipment (like the wall sockets) are typically excluded as well.

In getting a view on the constraints and potential of a technology system, there are *physical relations* which cannot be ignored. There are limits in a physical sense as involved in the availability of resources and land, for example, supplying soot filters to all cars in the world is not possible within a decade due to limitations in platinum supply.

In ISO-LCA, such physical constraints are not taken into account at present.

Currently, *environmental models* are included in the characterization step of the impact assessment. Fate and exposure models that have been developed by environmental scientists are used to express the pathways and degradation of chemicals in the environment. Population dynamics models are at present not often included, but at least an empirical rate of renewability is part of some of the characterization models.

Standard ISO-LCA does not take into account *economic relations*. However, a number of proposals and case studies have been published in which some micro-economic aspects are part of the analysis. For instance, Weidema (2000) and Ekvall and Weidema (2004) include shifts in market structure as part of the LCA inventory. Likewise, Hofstetter et al. (2006) and Thiesen et al. (2008) discuss the inclusion of rebound-effects. Inclusion of meso- and macro-economic models (modelling in terms of labour, capital, economic growth, spending etc.) is definitely beyond what is mentioned in ISO-LCA, and also what is done in typical LCA-studies nowadays.

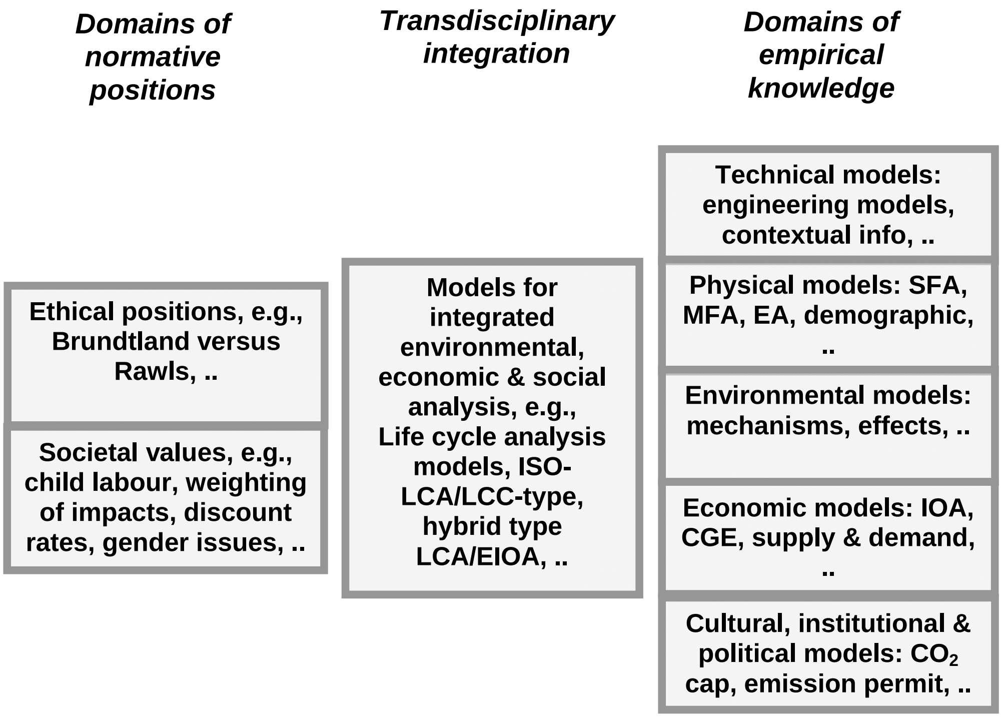

Figure 2: Deepening sustainability analysis of technology systems. Adapted from Huppes and Ishikawa (2009) and Heijungs et al. (2009)[12].

Socio-cultural, institutional and political models are not part of present-day LCA. They may be difficult to incorporate in the modelling framework anyhow. A typical place for this may be the stakeholder involvement around goal and scope definition and interpretation of ISO-LCA.

The most important normative element (*ethical positions and societal values*) in present-day LCA studies is weighting. Weights are sometimes derived from panel discussions or interviews, and sometimes from policy documents or monetary principles.

Models for integrated environmental, economic & social analysis are the place where we in fact find LCA, along with similar models, as an integrative framework. LCA as such does not address technical relationships, or environmental dose-response characteristics, or economic mechanisms. It only offers a carefully designed place for the integration of the disciplinary knowledge from these fields. Likewise, it offers a place to bring in normative positions in a clear and transparent way, but the normative positions themselves are not in any sense part of LCA.

2.1.4 The ISO-framework revisited

Building on Figure 2, a revision of the ISO-framework for LCA was presented in D15. In this framework for LCSA, it was tried to stick to the classic ISO-framework whenever possible, establishing the following correspondences (see Figure 3):

- question framing for sustainability decision support ⇔ Goal and scope definition

[12] Compared to Heijungs et al. (2009) micro-economic models and meso-/macro-economic models under “Domains of empirical knowledge” have been integrated into economic models; micro and macro models for integrated environmental, economic & social analysis have been integrated into models for integrated environmental, economic & social analysis; and ethical and societal values at micro and macro level have been split up into ethical values and societal values separately.

- technical models, physical models, environmental models, economic models, cultural, institutional and political models, ethical positions and societal values ⇔ Modelling ⇔ Inventory analysis & Impact assessment
- answers on sustainability questions ⇔ Interpretation

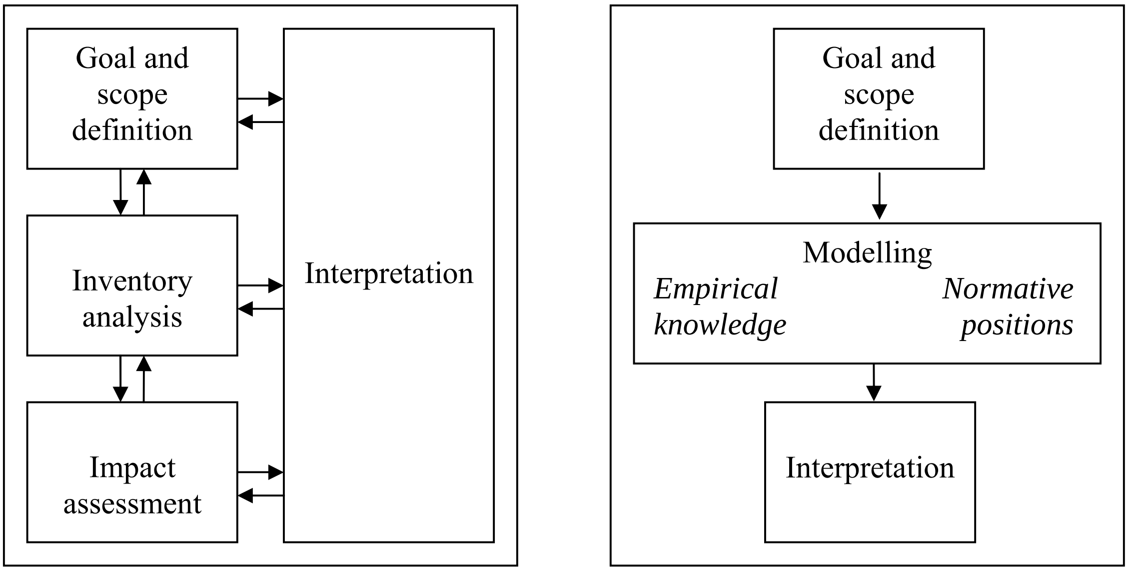

Figure 3: The ISO-framework (left) and the proposed framework for LCSA (right). The solid arrows in the LCSA framework indicate the major information flows only, whereas the arrows in the ISO-framework indicate both information flows and the iterative procedure of LCA.[13]

The two most striking things about this framework for LCSA are:
- it is very similar to the old framework for ISO-LCA[13];
- inventory analysis and impact assessment have merged into one modelling phase.

The first is a deliberate choice of terminology. Although "answers on sustainability questions" is a clearer term than "interpretation", we have tried to stay as close as possible to the well-known.

The second issue is more intricate. As shown in Section [2.1.2], and as has become clear during the last decade of academic work on agricultural production, climate change, impacts of land use, rebound and so on, it is difficult to make a clear separation between behaviour, technology, environmental processes, societal responses, and so on. Just a few examples:
- The fuel needed to drive one km with a certain car depends on technology, drive style, other traffic, traffic policy (speed ticketing) etc. So a seemingly technological parameter to specify a unit process depends on the entire complex of technical, physical, environmental, economic, and societal mechanisms.
- The climate impacts of a certain energy option depend not only on the technical characteristics of the life cycle of that product, but also on the background scenarios related to other industrial and household activities, as well as on the policy with respect to the mitigation of climate impacts, e.g. by means of the construction of dams and dykes.

[13] We don't want to deny the iterative nature of performing an LCA, on the contrary, but we do want to distinguish between these two different meanings of the arrows.

- The human toxic impacts due to PM10 releases of cars depend on obviously technical characteristics, like the engine design and the exhaust filters. But they also depend on human behaviour and public policy, with respect to, e.g., the distance between highways and residential areas, the part of the time people spend outside, the use of air quality control equipment in offices or houses, and many other issues.
- Mitigating measures, like the above mentioned filters and dykes, but also including drinking water purification and other established activities, are there to prevent certain impacts, but they cause certain impacts as well, because they require materials, energy, etc.

Altogether, there is no simple step from emissions (inventory analysis) to impacts (impact assessment), but there is a complex pathway of causes, effects, feedback loops, lag times, etc. In practice this means that deepened LCA/LCSA can no longer separate behaviour, technology, impact, and response, and hence can no longer follow the stepwise procedure of inventory analysis and a subsequent impact assessment. We might try to solve this by pointing to the iterative nature of the LCA process, where an initial inventory leads to an initial impact assessment, with feedback loops to a refined inventory with a refined impact assessment, and so on. This iterative structure has, however, been designed for a gradual improvement of quality: first a rough LCA, then a refined LCA, etc. For interwoven societal-environmental relationships, a fully integrated model may be required. A final issue of concern: does the merging of inventory analysis and impact assessment into one modelling phase imply that we have discarded the inventory table as a stand-alone intermediate result? No. Even when we take into account feedback from impact to activity, we may still in the end find out the total inventory table, containing entries on CO2, PM10, etc.

2.1.5 Environmental, economic and social LCA: mechanism, metric, and indicators

In this section, we focuses on the relation between the models for environmental LCA and forms of LCA that have a different scope, such as life cycle costing (LCC) and social life cycle assessment (SLCA). Klöpffer (2008, p.90) suggests in a conceptual formula that a life cycle sustainability assessment (LCSA) is an LCA, an LCC and an SLCA, done in a consecutive way:

$$LCSA = LCA + LCC + SLCA$$

In the field of combined LCA and LCC, quite some effort has been made to identify points of conflict in system definition, allocation, treatment of time, aggregation, etc. between these two tools (Hunkeler et al., 2008). Although we do not deny the importance of identifying and resolving such points of disagreement, there is one thing that we think has been neglected in these discussions. It is the idea that LCA and LCC should not merely have the same system definition, allocation, treatment of time, aggregation, etc., but that LCA and LCC represent two different ways of extracting performance indicators[14] from exactly the same system:

- LCA, LCC and SLCA have the same technological system - which we will call *technosystem*[15] from here on - as common basis;

[14] The term criterion might be preferred over indicator. An indicator should be linked to the concept intended to be measured and should be indicative of something else, requiring empirical validation. This mostly is not the case in the realm of sustainability analysis. Human health and economic affluence are relevant in themselves, not as an indicator for something then to be specified. Also, the term criterion directly links to subjects like multi-criteria analysis, which is required, in some form, in the interpretation of LCSA. As the term indicator is wide-spread within the LCA community, we will not change it now. We propose considering to replace indicator by criterion/criteria in a next revision round of the ISO standards.

[15] Technosystem refers to the technology or technological system that is analyzed. In ISO-LCA this is referred to as product system, but in LCSA this doesn't work anymore as it is not only products, but also sectors, markets or economies that serve as the starting point of analysis. As technology has a specific meaning, the choice has been made to refer to the basic system

- LCA, LCC and SLCA have different accounts that contain the information that is needed to address different indicators: environmental (emissions, resources, etc.), economic (employment, profit, etc.), and social (equity, public health, etc.).

Considered in this way, LCA, LCC and SLCA can be seen as three ways of looking at the same system. We have a technosystem that displays environmental, economic and social performance indicators when projected from different sides. Altogether, we should conceive the exercise to be carried out as the modelling of one single technosystem, containing the life cycle of the product under study, and the adding of performance information on environmental, economic and social data of the different unit processes in the technological system; see Figure 4.

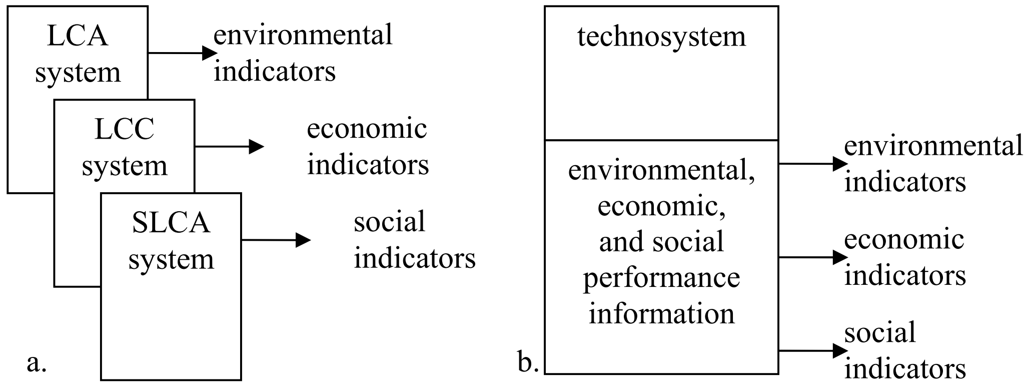

Figure 4: Redesign of environmental analysis (LCA), economic analysis (LCC), and social analysis (SLCA) as the sum of three separate analyses (a) into one analysis with three different sets of indicators (b).

One may doubt whether indeed LCA, LCC and SLCA can or should have the same technological system. After all, it is usual to include in LCC costs for R&D, while the impact of R&D are excluded in present-day LCA. And SLCA typically needs to indicators at a finer regional resolution than LCA and LCC. It is our conviction that from a theoretical perspective, all three analyses should have the same definition and specification. R&D should in principle be included in the LCA as well, and it is only for reasons of cut-off that it is excluded, whereas R&D may from a cost perspective be a substantial ingredient. Cut-off for practical reasons is, however, in no way binding. If the information is there, we may still add it, leading to small adjustments. Likewise, the finer resolution in SLCA can be carried out for the LCA and the LCC as well, and only be lost when aggregation into indicators takes place. With appropriate software, such a finer resolution provides no practical barriers.

Below, we will now define what the main limiting characteristics of ISO-LCA are in order to determine where LCSA starts.

2.2 Characteristics and constraints of ISO-LCA

Within the CALCAS project, the term ISO-LCA refers to all modes of LCA that are in line with the key features of ISO-LCA. According to ISO 14040(E) (2006), these key features are:

of analysis as *technosystem*. This term is also closely linked to technosphere (cf. Hofstetter, 1998), but to stress that LCSA is a system analysis we have changed this into technosystem.

4.3 Key features of an LCA

The following list summarizes some of the key features of the LCA methodology:

a) LCA assesses, in a systematic way, the environmental aspects and impacts of product systems, from raw material acquisition to final disposal, in accordance with the stated goal and scope;

b) the relative nature of LCA is due to the functional unit feature of the methodology;

c) the depth of detail and time frame of an LCA may vary to a large extent, depending on the goal and scope definition;

d) provisions are made, depending on the intended application of the LCA, to respect confidentiality and proprietary matters;

e) LCA methodology is open to the inclusion of new scientific findings and improvements in the state-of-the-art of the technique;

f) specific requirements are applied to LCA that are intended to be used in comparative assertions intended to be disclosed to the public;

g) there is no single method for conducting LCA. Organizations have the flexibility to implement LCA as established in this International Standard, in accordance with the intended application and the requirements of the organization;

h) LCA is different from many other techniques (such as environmental performance evaluation, environmental impact assessment and risk assessment) as it is a relative approach based on a functional unit; LCA may, however, use information gathered by these other techniques;

i) LCA addresses potential environmental impacts; LCA does not predict absolute or precise environmental impacts due to

   — the relative expression of potential environmental impacts to a reference unit,

   — the integration of environmental data over space and time,

   — the inherent uncertainty in modelling of environmental impacts, and

   — the fact that some possible environmental impacts are clearly future impacts;

j) the LCIA phase, in conjunction with other LCA phases, provides a system-wide perspective of environmental and resource issues for one or more product system(s);

k) LCIA assigns LCI results to impact categories; for each impact category, a life cycle impact category indicator is selected and the category indicator result (indicator result) is calculated; the collection of indicator results (LCIA results) or the LCIA profile provides information on the environmental issues associated with the inputs and outputs of the product system;

l) there is no scientific basis for reducing LCA results to a single overall score or number, since weighting requires value choices;

m) life cycle interpretation uses a systematic procedure to identify, qualify, check, evaluate and present the conclusions based on the findings of an LCA, in order to meet the requirements of the application as described in the goal and scope of the study;

n) life cycle interpretation uses an iterative procedure both within the interpretation phase and with the other phases of an LCA;

o) life cycle interpretation makes provisions for links between LCA and other techniques for environmental management by emphasizing the strengths and limits of an LCA in relation to its goal and scope definition.

Source: ISO 14040:2006(E), Clause 4.3, pp.8-9.

2.3 Life-cycle sustainability analysis (LCSA)

This ISO definition of LCA still gives plenty of room for interpretation and as stated under g) there is no single method for conducting LCA. However, there are also clearly some limitations to this ISO definition with respect to the domains of knowledge and the levels of deepening and broadening[16]:

- it has an *environmental focus only* ('broadening');
- it addresses *potential environmental impacts*;
- it *integrates environmental data over space and time*;
- it is *functional unit based*;
- it *focuses on a single product system* and its functional alternatives;
- it *focuses on the technology and environmental mechanisms* ('deepening') between the processes in the life cycle and doesn't include social, economic, cultural, institutional and political mechanisms.

As mentioned above, however, it is not that black & white. The points c), e) and g) offer sufficient room for interpretation. As LCC and consequential LCA have clearly surfaced since ISO-LCA and as they are applied more and more, we have stretched the boundaries of ISO-LCA to also include these two modes. Another reason for this is that we expect that short-term research can relatively easily and quickly bring progress and increase clarity[17] in these areas.

ISO-LCA is left, and thus LCSA starts, when we go beyond one or more of these limitations.

Going beyond can be done in several directions:

- Deepening:
    - going beyond the focus on technological, environmental mechanisms and also including other mechanisms such as physical, social, economic, cultural, institutional and political mechanisms (see Heijungs et al., 2009). In this direction the analysis may go beyond the ISO-LCA limitation "focus on the technology and environmental mechanisms" ('*deepening of the scope of mechanisms*');
    - going beyond the focus on currently adopted models reflecting aspects within these mechanisms[18], e.g., adopting spatially differentiated models. In this direction the analysis may go beyond the ISO-LCA limitations "potential environmental impacts" and "integration of environmental data over space and time" ('*deepening of a particular mechanism*').
- Broadening:
    - going beyond the focus on environmental aspects and also including economic and social aspects in the analysis of a system. In this direction the analysis may go beyond the ISO-LCA limitations "environmental focus only" ('*broadening the scope of indicators*');
    - going beyond the focus on individual product systems and taking sectors, baskets of commodities, markets, or whole economies, countries or the world as starting point of a life cycle analysis approach. From lower to higher level, we may go from product LCA, to meso LCA and eventually to economy-wide LCA for countries, for the EU (e.g., the EIPRO study by Tukker et al., 2006), for the OECD, for the Association of Southeast Asian Nations (ASEAN) etc. and eventually the world. In this direction the analysis may go beyond the ISO-LCA limitations "functional unit based" and "focus on a single product system" ('*broadening the object of analysis*').

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[16] Limitations of a more procedural nature are not considered here. For example, ISO 14040/14044 doesn't allow weighting for comparative assertions. This ISO-LCA limitation cannot be solved by more knowledge or better models (which is the focus of CALCAS WP7), but only by revising the ISO-Standard itself.

[17] Particularly in terms of when to apply it (for which type of questions and decisions) and how to perform it.

[18] Models and mechanisms are both used in this text in a mixed way. More strictly speaking, they are different and models reflect the mechanisms (more or less deepened, depending on the model).

After extensive reflections, we have arrived at a road map for life-cycle sustainability analysis (LCSA) that is shown in Figure 5. As announced in the introduction, the road map integrates all earlier structures and figures and starts by elaborating the procedural framework for LCSA in more detail. This elaboration is firstly made in terms of the two directions of broadening: '*broadening the scope of indicators*' and '*broadening the object of analysis*'. Deepening can be done in each box, either a technosystem box or an environmental, economic or social performance box. This is indicated by the symbol in each of these boxes. Deepening thus is at right angles to broadening in this Figure.

This and other characteristics of Figure 5 will be discussed in the next section.

2.4 Explanation of the proposed road map for LCSA

The left part of Figure 5 shows the procedural framework for LCSA as shown in Figure 3.
The right part of Figure 5 shows the elaboration in detail of the left part. Starting in the upper corner right, the Goal and Scope Definition phase is elaborated into a preliminary number of steps including "Framing the question for sustainability decision support", "Procedures", "Stakeholders", "Initial system boundaries", etc. Note that these steps are merely meant as illustration and not as final listing of steps of the Goal and Scope Definition of LCSA.
The second phase Modelling is elaborated in terms of the two directions of broadening ('*broadening the scope of indicators*' and '*broadening the object of analysis*'), and into a preliminary number of steps including "System boundaries", "Flow diagram", "Data & relationships between processes" (which now not necessarily have to be linear anymore), "Calculation (of inventory results, characterisation, ..)", "Interlinking models, variables or results" (e.g., from different scientific domains), etc. Also these steps are only meant as illustration and not as a final list. Three levels of analysis are distinguished:

1. product-oriented technosystem(s)
2. meso-level technosystem(s)
3. economy-wide technosystem(s).

Technological systems can thus be drafted at three different levels: product, meso or economy. Products are thereby defined as in the ISO 14040 Standards and comprise any goods or services. *Single products with the same function* are compared. An example could be the comparison of switch grass versus stover ethanol as biofuel. Meso refers to a level in between product and economy wide. It may include groups of related products and technologies, baskets of commodities (e.g., the product folio of a company), a municipality, a household, etc. An example question for this level might be the introduction of biomass as a major car fuel. Economy refers both to economies of states or other *geographical/political entities* including continents, the EU, the OECD, the ASEAN etc. and eventually the world. An example question for this level might be the comparison of options for technology domains, like for example strategies for phasing out fossil energy. The textbox below provides a non-exhaustive list of further examples.

Product-oriented questions:

- Choice of biomass for car fuel
- Product design (recycling oriented car design)

Meso-level questions:

- Second generation biomaterials & energy technologies
- Grid electricity based individual transport systems
- Research portfolio for sustainable technology development (also firms)
- Waste management and recycling systems

Economy-wide questions:

- Algae and artificial leaf based materials and energy
- Biobased economy
- Competition of land for food and fuel
- Decoupling economic growth from environmental degradation by selective constraints on consumption

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Multi-level questions:

- Biofuel potential
- Nuclear energy potential

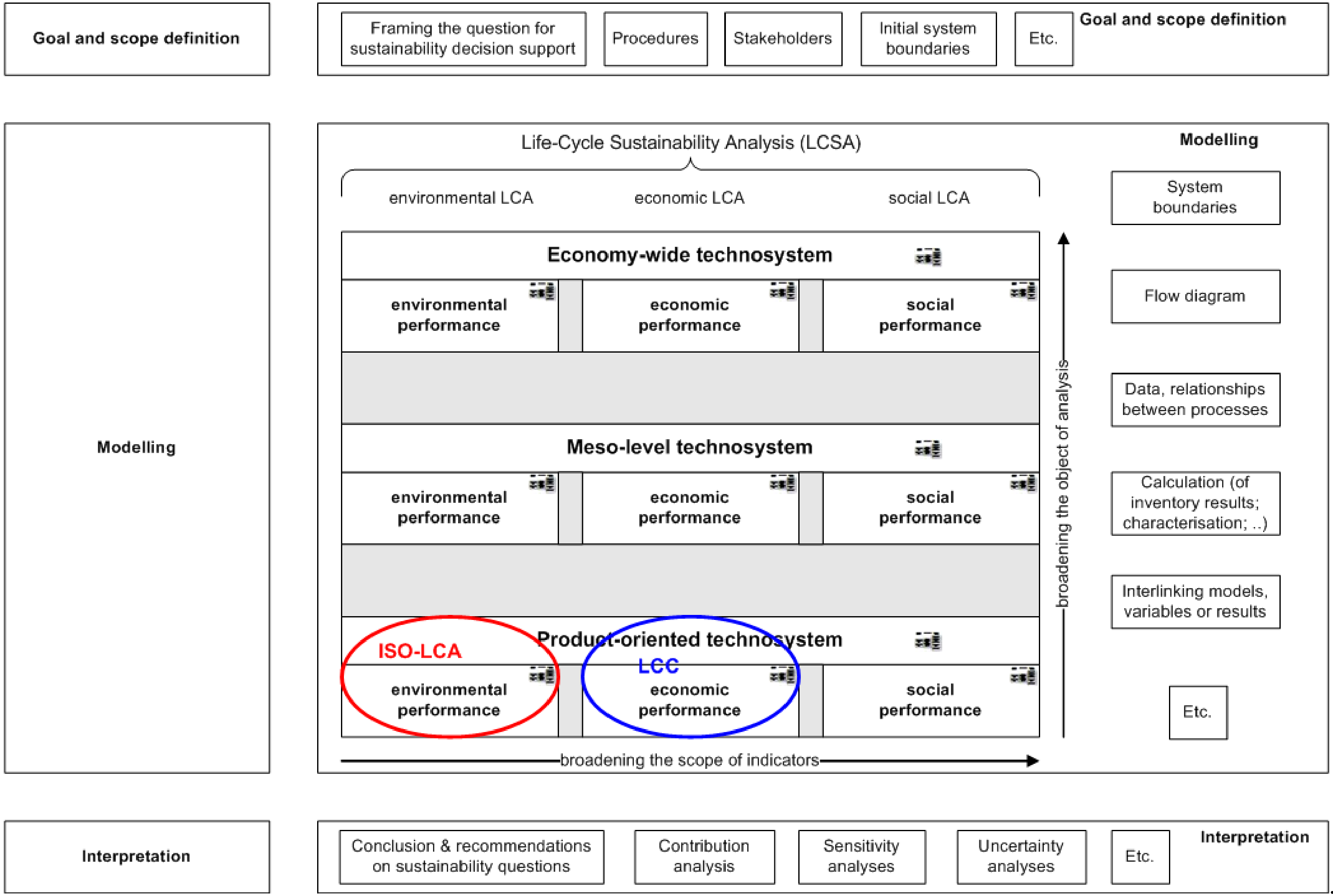


Figure 5: Road map for life-cycle sustainability analysis. Two ovals indicate the presently available ISO-LCA and LCC

The grey areas between the levels of analysis indicate that there may be some grey zone going from one level to the next.
The horizontal and vertical axes in Figure 5 reflect the possibilities for *broadening* the analysis. Technosystems are linked to at least one set of performance indicators (environmental, economic and/or social indicators). As a matter of speaking, these performance indicators dangle loosely to the technosystems.[19] A distinction is made between life-cycle analyses with just one set of performance indicators (environmental LCA, Life-Cycle Costing (LCC) and Social Life-cycle Assessment (SLCA)), and Life-cycle Sustainability Analysis comprising of performance indicators for all three (or at least two) pillars of sustainable development. The grey areas between the different sets of performance indicators indicate that there may be some grey zone going from one level to the next (cf. discussion on resource depletion being an environmental or an economic problem). Note that ISO-LCA and Life-Cycle Costing (LCC)[20] each are just *one* mode of analysis (if the modelling of a product-oriented technosystem and/or its environmental performance is deepened compared to the ISO-constraints listed in Section 2.2, it is not ISO-LCA anymore while we are still analysing a product-oriented technosystem and its environmental performance) in one of nine possible boxes for LCSA in Figure 5.
Broadening does not only refer to the “Modelling” phase of LCSA. Broadening is also part of the Goal and Scope Definition phase (how broad is the question at stake in terms of environmental, economic and social performance indicators considered) and of the Interpretation phase (for example, how to weight environmental performance against economic and social performance for a given technosystem).
Deepening can be done in each box in Figure 5, either a technosystem box or an environmental, economic or social performance box, with possible implications for each of the related steps. Figure 5 is thus actually the front of a three-dimensional structure. Deepening thus is at right angles to broadening. This is indicated by the symbol  in each of these boxes. Zooming in on this symbol shows us the main part (“framing the question and answering the question are skipped from the original Figure 2 as these are already mention in Figure 5) of Figure 2 again; see Figure 6.
In Figure 6, an example is shown of zooming in on the modelling of the product-oriented technosystem. Similar zooms can be made for all other boxes of Figure 5.

[19] This is why the performance boxes have been drafted with some space in between in Figure 5.
[20] Note that LCC is only about adding economic indicators (economic assessment) and not about modeling economic mechanisms or, in other words, only about broadening and not about deepening.

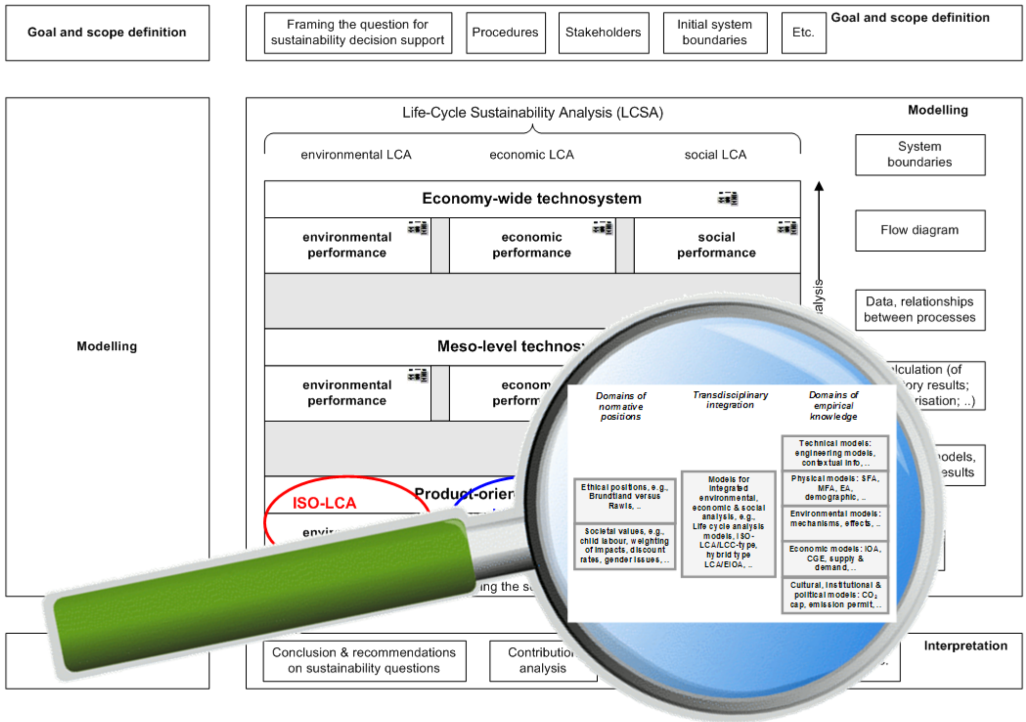


Figure 6: Deepening the analysis of a product-oriented technosystem

Note furthermore that the discussion on attributional and consequential modelling is an example of deepening in the current road map. In principle, consequential modelling can thus be relevant and applied at each of the three levels of analysis distinguished above. If there are sufficient motives to assume “full” *ceteris paribus* in a given case, then a practitioner can apply attributional modelling without hesitation.[21] If not, the practitioner should preferably go for consequential modelling. Although the discussion on attributional and consequential is a “deepening” discussion, it is clear that going from product to country, it will become more and more important to apply consequential modelling. On level 1, the assumption may often still hold but, going to level 2 and 3, the *ceteris paribus* assumption will have to be turned loose more and more.

Whereas Figure 5 functions as a sort of road map, helping a practitioner to find the appropriate object and scope of analysis for a certain question for sustainability decision support, Figure 6 more illustrates that an analysis of a give technological system can be made deeper and less deep, including all or just a selection of domains of empirical knowledge and using different methods and models available for each of these domains. As mentioned, Figure 5 and all possible variant of Figure 6 belong together and constitute together the road map for LCSA, integrating and elaborating the structure for deepening (Figure 2) and the framework for LCSA (Figure 3).

Extensive discussion is still possible on the both Figure 5 and Figure 6, but these cannot be held as part of the CALCAS project. It therefore seems wise to include a topic on the further refinement of these structures as part of the CALCAS research recommendations.

The LCSA framework defines the procedure in three steps (goal and scope definition, modelling, interpretation) as it will be described in the report of the specific assessment study; but, as well known, a LCA study is based on an iterative process, specifically in the most complex cases. Moreover, the combination/integration of different knowledge domains and models, as required in LCSA, must be based on detailed analysis of equivalence, consistency, coherence, comparability across different scales of time and space, with related problems of data flow etc. For that, it could

[21] The assumption of *ceteris paribus* is often applied in product assessments. It means that the choice of the functional unit of the product alternative investigated has no influence on any other activities anywhere on the planet. For example, this means that the effects of the emissions due to the functional unit are assumed to be additional to the normal background concentration. The functional unit was also assumed to be marginal relative to other activities, allowing linear models to be used (Guinée et al., 2002).

be useful to also exploit a working method helping to work with Figure 5, framing the question, selecting appropriate methods, models, and applying them, in three phases:

- a “semantic” analysis,
- a “syntactic” analysis, and
- an “operational” analysis.

This working method gives some suggestions on how to manage the fundamental phase of the integration of the models inside the Figure 5 by an iterative process.

Semantic analysis might comprise of the following steps:

- the question and decisions at stake
- qualitative description of the technological options and systems considered, identification of their main interrelations (synergies, conflicts, trade-offs, etc.) between the object analysed and the surrounding objects and between the environmental, economic and social domains for the question at stake, etc.;
- qualitative assessment of the expected impact of the decision: what is the scale of expected changes, to what extent may a *ceteris paribus* assumption may hold or not, etc.;
- identification of the relevant domains of knowledge to be included (mechanisms to be modelled);
- determination of the most appropriate object of analysis, considered indicators and considered mechanisms and the required depth of analyzing these mechanisms.

The syntactic and operational analysis could be considered the working method of the technosystem and performance indicators boxes in Figure 5, and might comprise of the following steps:

Syntactic analysis:

- identification and selection of available methods and models for the required depth of analysis of knowledge domains considered and for the (hard or soft) integration among them;
- analysis of data availability and reliability for the identified models;
- identification of modelling gaps (i.e. mechanisms not fully addressed by the available models) and strategies to bridge them;
- identification of the control systems;

Operational analysis:

- application of selected models;
- verification of the numeric results in terms of acceptability of uncertainty level, agreement with the initial expectations, etc.

2.5 Semantic analysis: framing the question

The box on “Framing the question for sustainability decision support” in Figure 2 and Figure 5 is always the starting point of any analysis. Framing the question is a very important activity. An erroneously framed question will get an erroneous answer. Framing the question, amongst other things, means that we ask ourselves in depth what exactly the problem is that we are trying to tackle, what the derived questions are, what the technological options are, what the scale of expected changes is, if a *ceteris paribus* assumption may hold or not, etc. For example, a study on biofuels may lead – and has done so in practice already – to various levels of analysis and the use of various methods and models depending on this question framing. If we pose the question in terms of “to what extent can we supply our global road transport energy needs in a sustainable way with biofuels”, we are likely to end up performing the analysis on the level of an economy-wide technosystem with all three sets of performance indicators, running land use models, food models, IO based LCA models, etc. On the other hand, if we pose the question in terms of “is Jatropha-based biodiesel cultivated on set-aside land at a Brasilian farm for local use more sustainable than fossil-based diesel”, we might end up performing a product-oriented (ISO)-LCA, possibly replenished with LCC and that is it. One always has to wonder what the expected impact of the decision at hand is: if the system analyzed is only replacing one other system on a small (local) scale, the lowest object of analysis in Figure 5 might give a sufficiently sensible answer; if it is expected that the technology used in the new system will probably expand to many more applications on a larger scale, the analysis will have to be risen to a higher (meso or economy) level. Question framing is thus very important, and it is a general research issue to identify what help science can offer and what help experiences with real (e.g. bio-energy) cases can offer in setting some guidelines for question framing.

Question framing intends to unravel the starting sustainability question into questions for, whenever relevant, each of the three different "object of analysis" levels. Sometimes, of course, questions may refer to one level only, but let's suppose we have a starting question that can be transposed into one or more questions for each object of analysis. Questions and object of analysis are then highly interlinked and the models adopted and the deepening strived for together determine the exact technosystem analysed. The same holds for the performance indicators: question and object of analysis determine which models and which indicators are adopted etc. A scheme linking question and object of analysis to answers by models/indicators could look like Table 1.

Table 1: Linking question and object of analysis to answers by models/indicators

	a. Answer on product level	b. Answer on meso level	c. Answer at economy-wide level
1. Question on product level	Level 1 models/indicators (e.g., ISO process-LCA, hybrid LCA, ..)	Level 1 models replenished with level 2 models	Level 1 models replenished with level 3 models (e.g., up scaling of product LCA results to economy-wide level taking into account, e.g., models on physical constraints of resources, land use etc.)
2. Question on meso level	X	Level 2 models/indicators (e.g., LCA for a market including all products of that market, EU IOA model for product group prioritization like in the EIPRO study, ...)	Level 2 models replenished with level 3 models
3. Question on economy level	X	X	Level 3 models/indicators (e.g., IO-LCA for an economy ...)

X = Increased risk of wrong answers

It seems to make some sense that the diagonal of this table indicates the preferred choice of models/indicators for the various levels of questions, but this is not current practice and will therefore certainly be debated. It is clear that *more work and research* may have to be done in this area first, before the above table can be better founded and filled in further.

2.6 Syntactic analysis: models and methods for LCSA

Following the first step of the analysis, *Framing the question*, the next one consists of the selection of the most appropriate models to perform the LCSA in the specific context. This step cannot be generalised because a plethora of methods and models is available, each of them developed and suited for a specific application. For this reason, this section is aimed at supporting a syntactic analysis by making available a list of models, with the information and knowledge they provides and highlighting elements for combination/integration among models in the LCSA framework in a way they complement each other and provide coherent, relevant, reliable and complete outputs or they show gaps.

This information is provided making use of the template described in Table 2, in which the following elements are outlined for each model (EEA, 2008):

<u>Main features</u>

- *Level of answers* (product, meso, economy-wide). Models have features that make them suitable for providing answers at specific levels, e.g. EW-MFA has the optimal resolution at national level (economy-wide applications). As the LCSA framework requires to take into consideration the relevant mechanisms at all levels, it is of interest mapping the models against the boxes of the framework.
- *Thematic coverage.* Themes addressed by the model (e.g. biodiversity, resources, energy, climate change, etc.).
- *Scientific background and principles.* Main principles governing the models (e.g. thermodynamic laws).

<u>Modelling features</u>

- *Geographical coverage*. The geographical extent to which the models operate on and provide output for, and the related spatial resolution.
- *Temporal coverage*. The time horizon considered in the analysis by the method/model.
- *Analytical technique*. The kind of model used (accounting system vs. modelling system), the analytical technique applied (steady-state, dynamic model, equilibrium model, etc.), the computational structure. Moreover, input (key input parameters used by the model), output (main output variables or indicators) are of interest for identifying possible linkages among models and, since the unavailability of (reliable) data prevents from any possible application of the model, data quality and availability is also included in the analysis.
- *Mechanisms addressed*. The empirical mechanisms covered, besides the one identified as primary for the models analysed.

<u>Sustainability domains</u>

Focus is on analysing the present field of application of the model (environmental, economic, and social pillar).

Table 2 – Template for the analysis of the models

	Model/method 1	**Model/method 2**	**Model/method 3**	**Model/method n**
MAIN FEATURES				
Level of answers				
- Product				
- Meso				
- Economy-wide				
Thematic coverage				
Governing principles				
MODELLING				
Geographical coverage				
Temporal coverage				
Mechanisms addressed				
- Technological rel.				
- Environmental mec.				
- Physical rel.				
- micro-economic rel.				
- Meso/macro-econ. rel.				
- Social, cultural & political rel.				
Analytical technique				
- Model features				
- Data				
- Input				
- Output				
SUSTAINABILITY DOMAINS				
Environmental aspects				

Economic aspects				
Social aspects				

In the following paragraphs the models are analysed according to the mechanisms they address: Technological relations, Physical relations, Environmental mechanisms, Economic relations. An exemplification of the mechanisms in a sustainability analysis is available in Annex 2. In the case of Physical relations, the specific relevance for LCSA has been also outlined from a general perspective.
A detailed description of all models is available in Schepelmann et al. (2008).

2.6.1 Technological relations

Technological relations describe the principal causal relationships that connect the level of two economic activities.
Among the numerous models inventoried, those that have been identified as applicable for the description of the technological relations are the following:

- Life Cycle Costing (LCC)
- Total Cost Accounting (TCA)
- Total Cost of Ownership (TCO)
- Hybrid Analysis
- Life Cycle Activity Analysis (LCAA)
- Life Cycle Optimisation (LCO)
- Social Life Cycle Assessment (SLCA)
- Carbon Footprint (CF)
- Environmental Risk Analysis (RA)

Their analysis is provided in Table 3

Table 3 – Models based on technological relations

	LCC	TCA	TCO	Hybrid Analysis	LCAA	LCO	SLCA	CF	RA
MAIN FEATURES									
Level of answers									
- Product	√	√	√	√	√	√	√	√	√
- Meso				√				√	
- Economy-wide								√	√
Thematic coverage	Costs of the whole life cycle of a product/service	Profitability of business investment and operations.	Direct and indirect costs related to the purchase of a product	Environmental impacts	Economic and environmental optimization of the supply chain	Life cycle optimisation on environmental, technical and economic.	Social aspects throughout the product life cycle	Greenhouse gases	Environmental and/or health and safety risks
Governing principles	FU-based analysis	Profitability	?	?	Optimisation principle	Multi-objective optimisation	FU-based analysis	FU-based analysis	?
MODELLING FEATURES									
Geographical coverage	For a specified place	For a specified place	For a specified place	For a specified place	For a specified place	For a specified place	For a specified place	For a specified place	For a specified place
Temporal coverage	For a specified time	For a specified time. Incorporation of the time value of money.	For a specified time	For a specified time	For a specified time	For a specified time	For a specified time	For a specified time	?
Mechanisms addressed									
- Environmental mec.				√ (in the characterisation phase)	√ (in the characterisation phase)	√ (in the characterisation phase)		√ (in the characterisation phase)	√
- Economic rel.									
- Social, cultural & political rel.									
Analytical technique									
- Model features	Linear, steady-state model	Cost accounting method; producer-perspective	Management accounting method; perspective of product user/consumer	Comparative-static, without dynamics, spatial resolution and non-linearities	Numerical technique, based on the input-output table format. Equilibrium between	Materials accounting methods + optimisation techniques + multicriteria analysis	Linear, steady-state model	Several models can be used, mainly linear, steady-state models, with different computational	Probability theory and methods for identifying causal links between adverse effects

	LCC	TCA	TCO	Hybrid Analysis	LCAA	LCO	SLCA	CF	RA
					demand and supply and all relationships are assumed to be linear.			structure (LCA; EIOA, etc.)	and different types of hazardous activities
- Data	All costs associated within the life cycle directly covered by one, or more, of the actors involved + external costs that are anticipated to be internalised.	Direct and indirect costs, contingent and liability costs, intangible costs, external costs.	Purchase and related costs (ordering, delivery, usage, maintenance, supplier costs, after-delivery costs).	Integration of process-based and EIO-based LCA data. Inherent limitations related to IO data	Physical and monetary flows	Physical quantities on product, process and socio-economic aspects	Physical quantities related to the product + info on organisation-related aspects along the chain. Problem of data availability reliability.	Physical quantities on product/service/ etc.; emissions (direct and indirect) limited to greenhouse gases	The minimum set of data required depends on the use category, regulation involved and the goal of RA: Examples for RA of chemicals: identity of the substance, its physicochemica l, tox and ecotox properties, its uses, emissions and exposure.
- Input									
- Output									
SUSTAINABILITY DOMAINS									
Environmental				√	√	√		√ (only climate change)	√
Economic	√	√	√		√	?			√ (socio-economic indicators)
Social							√		

2.6.2 Physical relations

Physical relations and constraints refer to the inherent limitation of material and energy of the natural system, and are related to exhaustion of raw material supplies and the accumulation of substances in the environment. They are a fundamental element to be considered and at the same time very useful control parameters in performing sustainability evaluation.
Considering physical constraints (and the options for intervention, where constraints are small or absent) in the LCSA framework presents the following features:

- they highlight that economic activities do not take place in a closed system, but in an open one that exchanges material and energy with its environment;
- they provide a clear link with economic models, with an increased value for the study of long term effects (role of stocks and flows in the economic systems);
- they allow analysing the concept of substitution in a physical dimension;
- stocks and flows deeply affect a realistic representation of the dynamics of technological changes (Van den Bergh and Janssen, 2004).

The models which give contributions to the analysis of physical relations are:

- Economy-wide Material Flow Analysis (EW-MFA)
- Substance Flow Analysis (SFA)
- Material Input Per unit of Service (MIPS)
- Energy/Exergy Analysis (EA).

Table 4 – Methods and models for the physical relations

	EW-MFA	SFA	MIPS	EA
MAIN FEATURES				
Level of answers				
- Product		√ (substances)	√	√
- Meso				√
- Economy-wide	√	√ (economies)		√
Thematic coverage	Materials availability (material input and output)	Materials availability (substances)	Materials availability (primary resources extraction)	Energy
Governing principles	Mass balance principle	Mass balance principle	Mass balance principle	Thermodynamic principle
MODELLING FEATURES				
Geographical coverage	Region or country. Depending on data availability, resolution can be obtained: regional scale, community, company level.	Specific place, geographically demarcated system (country, city, plant, etc.)	Specific place	Specific place, geographically demarcated system with different resolution depending on data availability
Temporal coverage	Specific time span, e.g. one year	Specific time span (normally one year)	Specific time span	Specific time span
Mechanisms addressed				
- Technological rel.	√	√	√	√
- Environmental mec.				
- Economic rel.				
- Social, cultural & political rel.				
Analytical technique				
- Model features	Accounting system Computational structure similar to	Modelling technique: - static - quasi-dynamic	Accounting system	?

	EW-MFA	SFA	MIPS	EA
	input-output analysis	- dynamic Computational structure similar to input-output analysis		
- Data	Data available from statistics. Inherent limitations related to update, comparability among tables of different countries, etc.	Data available from statistics. Difficulties related to the great variety of substances and their properties. For a dynamic model time series data and information on stocks are needed. This is a time consuming activity that poses difficulties at statistical level	Limited data quality and availability	?
- Input	Material inflows and outflows; imports and exports; indirect flows; emissions and wastes.	Inflows and outflows of the specific substance analysed	Quantity of resources used for a specific product or service.	
- Output	Bulk material flows balance through society	Detection of the substance pathway	Material Input, i.e. total amount of material required for the product/service analysed	
SUSTAINABILITY DOMAINS				
Environmental aspects	Environmental pressure (emissions, extractions, etc.) Resource-consumption indicators can be derived.	Environmental pressure indicators. Input for further analysis.	Environmental pressure indicators.	√
Economic aspects				?
Social aspects				

2.6.3 Environmental mechanisms

The environmental mechanisms considered are those included in the characterisation step of Life Cycle Impact Assessment methodology. They have been extensively analysed in two main documents:

- the ILCD Handbook, in particular the Guidance document for LCIA models, methods and factors (Hauschild et al., 2008b);
- the critical review on ISO-LCA, in which the main research needs and developments have been identified for each phase of the LCA methodology (Zamagni et al., 2008).

The main outcomes of these documents have been summarised in section 4.
In this specific case, the template has not been applied as the models have not been analysed from the analytical viewpoint, but only to the extent they are used in the LCA methodology.

2.6.4 Economic relations

They include both micro-economic relations, including rebound effects, and macro-economic relations. The following models have been analysed:

- Computable General Equilibrium model (CGE)
- Input Output Analysis (IO)
- Environmentally Extended Input Output Analysis (EE-IOA)
- Partial Equilibrium Models (PEM)

Indeed, this choice can be questionable because the IO is the model underlying both EE-IOA and CGE. Nevertheless, for the sake of simplicity and because each of them can be applied for different purposes, they have been analysed separately.

Table 5 – Models based on economic relations

	CGE models	IO	EE-IOA	PEM
MAIN FEATURES				
Level of answers				
- Product				√
- Meso		√	√	√
- Economy-wide	√	√	√	√
Thematic coverage	Broad spectrum in the fields of energy, environment and economic policies.	Inter-industry/sector transactions	Inter-industry/sector transactions with environmental dimension	Different thematic coverage, depending on the sectors investigated: agriculture, climate change, land use, water, etc.
Governing principles	Market equilibrium	Balance between the total input and the aggregate output of each commodity and service produced and consumed	Linearity for environmental interventions, as for technologies in IO, general equilibrium between supply and demand.	Supply and demand balance described through changes in price.
MODELLING				
Geographical coverage	Country, world (the whole economy)	Nation, region	Nation, region	Global and EU, with different degrees of resolutions (regions, countries, and also smaller aggregates.)

	CGE models	IO	EE-IOA	PEM
Temporal coverage	The time horizon depends on the specific model..	Specified time	Specified time	Usually the time steps are annual, while the time horizon depends on the specific model.
Mechanisms addressed				
- Technological rel.	?			?
- Environmental mec.	?			
- Physical rel.	?			?
- Social, cultural & political rel.	√			√
Analytical technique				
- Model features	Comparative-static; Dynamic equilibrium models; Quasi-dynamic models.	Static accounting system, based on linear dependencies, giving constant scaling, ass. of general equilibrium	Static accounting system, based on linear dependencies, giving constant scaling, ass. of general equilibrium	Partial equilibrium modelling
- Data	Data structure of national/EU accounts (IOT), available from statistics, plus data derived from empirical data and econometric models.	Data structure of national/EU accounts (IOT), available from statistics	IO-tables and environmental data, available from statistics,	Data structure of national/EU accounts (IOT), available from statistics
- Input	Tables of transaction values (IOT or SAM); elasticities; environmental data on emissions		At EU level EE-IO tables are still limited to few emissions to air. More comprehensive EU-wide EE-IO tables are expected By EXIOPOL project.	Prices, physical data (according to the sector analyzed), activity level data, policies, etc.
- Output	Examples of variables used, not representative of the full range of CGE models: evaluation of distributional effects, atmospheric emissions, pollution abatement capital, etc.			Depending on the specific sectors, different outputs param. can be used to quantify effects of decisions on the price and flow of specific materials, products and services.
SUSTAINABILITY DOMAINS				
Environmental aspects	Environmental pressure (emissions), environmental impacts (e.g. global warming, public health, etc)		√ (Environmental pressure)	Environmental pressure (emissions), when addressed.
Economic aspects	√	√		√
Social aspects	Only partially addressed (few indicators, depending on the specific model)			Addressed only by few models, with few indicators

2.6.5 Aligning methods and models in the LCSA framework

A further analysis on the methods, mapping them against the LCSA framework, can give us additional information, from one hand, on major gaps, i.e. boxes of the LCSA framework for which the analysis is hampered by the lack of models, and, on the other hand, on possible overlaps among models. This second aspect can be useful in many respects: possible linkages, use of one model as control for the results of another, etc. Of course this mapping is a very generic and "virtual" exercise, because this analysis can be really exploited only when addressing a specific case study. As always in such compilations, methods in different stages of development overlapping with each others (e.g. MIPS and LCI) or incompatible with each other are listed together.

The results of the mapping are showed in Table 7, in which:

- green symbols refer to models covering the environmental performance box;
- blue symbols refer to models covering the economic performance box;
- pink symbols refer to models covering the social performance box;
- yellow symbols refer to models which cover more than one performance box and level of the analysis. For example, CBA can be applied at product, meso and economy-wide level, and in principle provides information on all the three performance boxes.

The list of abbreviations used is available in Table 6.

Table 6 – List of abbreviations used in the table

Abbreviations		Abbreviations	
CBA	Cost Benefit Analysis	**MCA**	Multi Criteria Analysis
CF	Carbon Footprint	**MIPS**	Material Input Per unit of Service
CGEM	Computable General Equilibrium Model	**PEM**	Partial Equilibrium Model
EA	Energy/Exergy Analysis	**POEMS**	Product Oriented Environmental Management System
EE	Eco-Efficiency Analysis	**RA**	Risk Analysis
EE-IOA/IOA	Environmental Extended Input-Output analysis	**SA**	Sustainability Assessment
EIA	Environmental Impact Assessment	**SEA**	Strategic Environmental Assessment
ExE	ExternE	**SFA**	Substance Flow Analysis
EW-MFA	Economy-wide Material Flow Analysis	**SLCA**	Social Life Cycle Assessment
LCAA	Life Cycle Activity Analysis	**SPD**	Sustainable Process Design
LCC	Life Cycle Costing	**TCA**	Total Cost Accounting
LCO	Life Cycle Optimisation	**TCO**	Total Cost of Ownership

From the analysis of Table 7 the following general considerations come out:

- **Level of coverage of performance boxes**
    - The economic and environmental boxes are well covered: several models exist, which vary in scope and concepts. This variety of models seem to be necessary, because allow different answers for different level of questions, and even within the same level they are suited to different users' perspective. For example, at the level of product-oriented technosystem, in case of an investigation with consumer perspective LCC can be exchanged by TCO (Schepelmann et al., 2009).
    - The social performance box results not well addressed. This result can be biased by the fact that indeed, in CALCAS the social domain has not been analysed in detail. Besides analytical methods, there are also procedural framework[22] which can provide evaluations on social aspects, like Sustainable Process Design, and others like Environmental Impact

[22] Procedural framework have not been included in the analysis of the mechanisms, as explained in paragraph 4.3

Assessment, Strategic Environmental Assessment, Cost Benefit Analysis and Multi Criteria Analysis, which integrate participative methods for assessing social aspects.

- **Level of coverage of mechanisms**
  With the exception of cultural, institutional & political relations, which have not been analysed, the models cover the entire spectrum of mechanisms and relations.

- **Consistency among levels and interactions among models**
  Many models do not cover only a specific box in a defined level (product, meso and economy-wide), but the following situations occur:
  - models that are in between environmental and economic performance boxes
  - models that are both vertical and horizontal to the structure i.e. cover all the levels and at least two performance boxes
  - models that provide answers at the three levels
  - several models in the same box (mainly the environmental one), which show complementarities and then, leave space for integration.

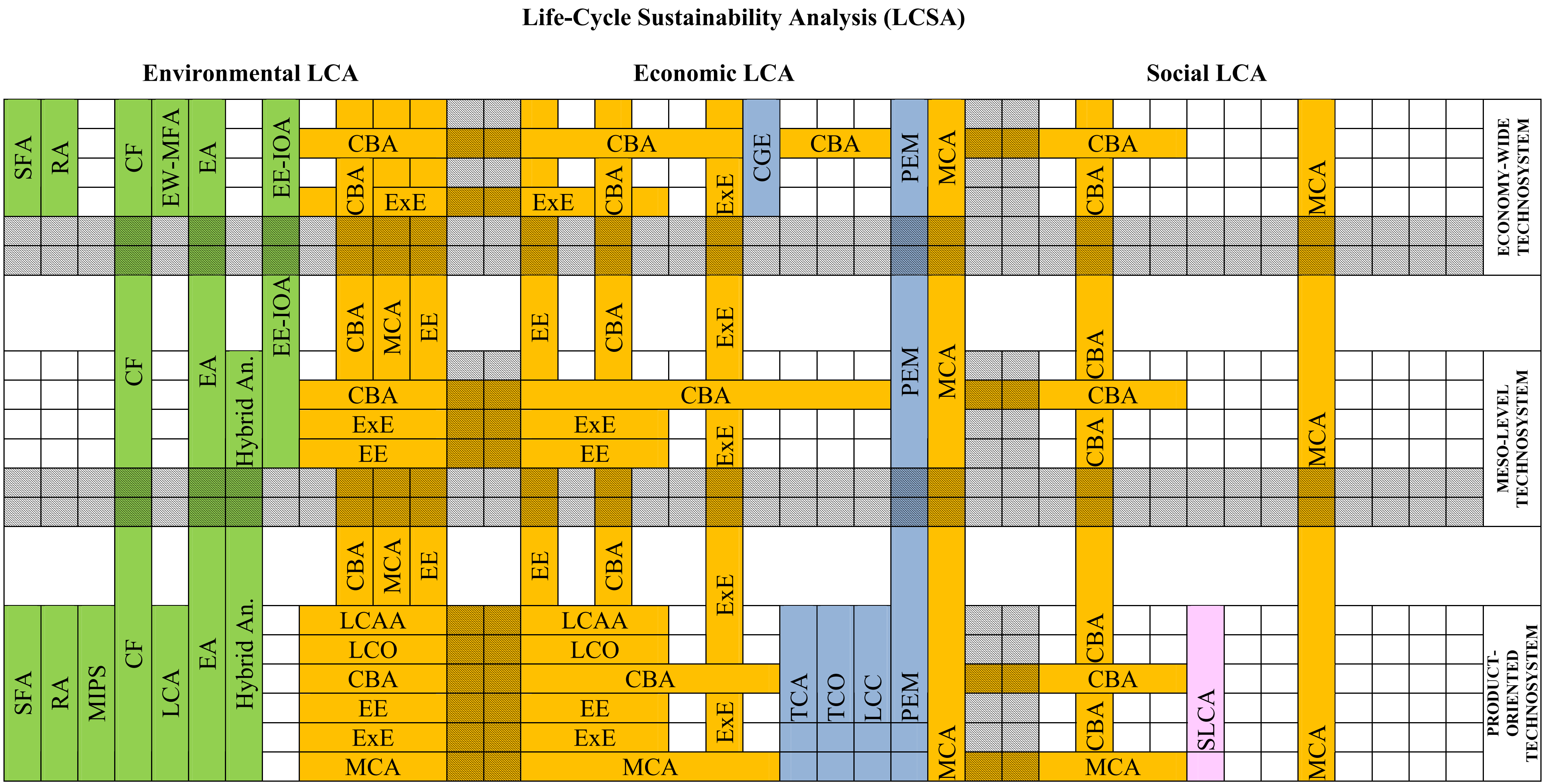
Aligning the models in the LCSA framework, as preliminary step to define a step wise procedure for the operative implementation of the analysis, would require understanding how the models link up each other in a coherent way. This correspondence among models can be established at two levels:

- Information flows, in order to broaden the scope of indicators (within the same box and among different boxes);
- data structure and modelling technique, as elements that could make easier the integration among models and thus deepen a particular mechanism (or the scope of mechanisms) and broaden the object of the analysis.

It would be of interest to analyse such opportunities for integration, but certainly this cannot be done at general level and for all models: indeed, this would result in an abstract exercise because the use of specific models is guided by specific questions[23]. The case studies of the following section provide examples of possible linkages among different models

[23] The table 6 and similar can be read also at general level as a way for stimulating suggestions for further deepening of modeling in the iterative process of LCSA. Moreover, the mapping of accumulated and overlapped different case studies could provide a sort of "expert" system able to supply information on the reliability of the adopted solutions and to understand if and how to apply "*puzzle*" or "*sudoku*" effects for the empty zones.

Table 7 – Map of methods and models in the LCSA framework



3 Examples of applications

Below three examples of LCSA are provided and discussed. The first, most extensively described, example concerns a theoretical case on biofuels. The second and third examples are derived from real cases on respectively waste management and diet changes and are described more briefly.

3.1 Example 1: biofuels

In this section, we illustrate the Goal and scope definition (G&SD) of an LCSA on biofuels. Another example, compliant with the LCSA framework, can be found in (Huppes and Ishikawa, 2009). The case study here described is a comparison of different options for Swedish production of biofuel to replace 25% of the fossil vehicle propellants in Sweden in the year 2030. We assume it is commissioned by a Swedish oil company in pursuit of sustainable options for long-term future business opportunities.

The LCSA framework includes a large number of steps, methods and models (see Figure 2). As indicated above, it is not feasible and often not relevant to apply all types of methods and models in an individual case study. The choice of methods depends on how the question is framed: what decision is at hand, which derived questions can be drafted, what sustainability aspects are most important for this decision, and what mechanisms decide the metric for each of the important sustainability aspects. Identifying these fundamental features of the study is a procedure that requires participants with a broad combined expertise and, preferably, a broad representation of views and interests. This means that LCSA integrates elements from participatory methods into the predominantly quantitative analysis (see Section 2).

Relevant stakeholders in this case study include, but might not be restricted to:

- the oil company itself, represented by, e.g., individuals from the general management, environmental management, marketing department, and/or engineers,
- consumers of propellants, represented by, e.g., the Swedish Automobile Association and the Transport Group,
- car, truck and/or bus manufacturers, since the biofuel option might need modifications in the production of vehicles,
- national authorities, such as the Environmental Protection Agency, since the biofuel option might need governmental subsidies and/or infrastructure investments to be viable, and
- environmental non-governmental organisations (NGOs), represented by, e.g., individuals from the Swedish Society for Nature Conservation and/or Greenpeace,

These can be invited to a G&SD workshop to increase the likelihood that the stakeholders accept the results of the LCSA as relevant basis for decisions on biofuels in the transport sector. At this workshop, the LCSA practitioners guide the stakeholders through a series of brainstorming and selection exercises to identify 1) the questions and decisions 2) objects of the study, 3) the most significant sustainability aspects, 4) the most important mechanisms etc. that decide the outcome for each sustainability aspects, and 5) the relevant options for modelling the mechanisms and/or assessing the sustainability aspects.

3.1.1 Question framing

As discussed in Section 0, question framing intends to unravel the starting sustainability question into questions for, whenever relevant, each of the three different “object of analysis” levels. In this case the starting question concerns the “comparison of different options for Swedish production of biofuel to replace 25% of the fossil vehicle propellants in Sweden in the year 2030”. The way this question is formulated, we may easily end up performing the analysis on the level of an economy-wide technosystem with all three sets of performance indicators, running land use models, food models, IO based LCA models, etc. Basically, large-scale production of biofuel is likely to affect Swedish land-use. Since Sweden is part of an open global market, a change in Swedish land-use is likely to affect exports and imports of other products from agriculture and/or forestry. This might affect the cutting of tropical rainforest, the competition with land for food production[24], etc.

Although the starting question is restricted to a single country it is, in fact, not a local question aiming at full self-sufficiency. From the starting question, we can derive questions at the product level (which biofuel is environmentally, economically and/or socially benign), at the meso-level (how is the food-sector affected by the biofuel sector) and even at economy-wide level (what are the physical limits of land use for food, biomaterial and biofuel production). See also the textbox in Section 1.4 for additional, possible questions for the biofuel case.

The outcomes of this question framing determine all subsequent choices with respect to decisions supported and not supported objects of analysis, sustainability indicators and mechanisms included. In this theoretical example the question framing is done as a mental exercise and we refrain from any further results. In the textbox below, a non-exhaustive list of possible (other) questions for this biofuel case is provided.

[24] Biofuel stimulating policies haven proven to be an incentive for an economic restructuring of the agricultural sector (changes from food to biofuel production), which was for example included with a partial equilibrium model (CAPRI) in a study on diet changes (see Section 3.3).

Questions determine how answers are generated
Principles for posing questions: Case examples

- Questions from real life answered with "most appropriate means".
- Questions formulated independent of options for answering (as much as possible)
- As soon as a question of a more limited nature can be seen only as a part of a more general question, the more general questions should be answered, possibly with a focus on the more restricted question.
- In principle full sustainability scope; what not is relevant comes out as a result.

Case Biomass for Biofuel: Questions to be answered

1. Should I fill my car today with gasoline or with E85 (alcohol fuel mixture of approximately 85% denatured fuel ethanol and 15% gasoline/other hydrocarbon by volume)?
2. Should I buy a car tomorrow fit for using ethanol as a major fuel?
3. Should I, as a car producer, develop ethanol cars, or hydrogen cars, or plug-in hybrids, or fuel cell cars, or battery driven electric cars, or all of most of these options?
4. Should Sweden (or Denmark; or Iceland; or China) shift to 25% biofuel for road transport? At which time horizons?
5. For second generation biofuels, should we use switch grass, sugar cane bagasse, corn stover, or …. as the major biomass feedstock for biofuel production? Would regional characteristics make a small or major difference?
6. Should the richest countries endorse on a path to biofuels as the major fuel for mobile applications in the medium term of two decades? Would you reckon with carbon capture and sequestration in comparing with fossil fuels?
7. Should we as Western society go for one of the options, or a mix of options in terms of ethanol cars, hydrogen cars, fuel cell cars, plug in hybrids or full electric cars (etc)?
8. Should the world endorse on a path to biofuels as major fuel for mobile applications?
9. Should we use biomass in the most advantageous energy applications, including incineration, gasification and biotech based transformations?
10. Should we shift to a bio-based society, for both energy and materials?

Finally, note that even more and deeper reasoning on mechanisms might be useful to include in a study of the pros and cons of biofuels (see Annex 2).

3.1.2 Objects of the study

The object of study for each biofuel includes most important sources and applications of the fuel. To be important, they must be realistic and large enough to matter in a system that replaces 25% of Swedish fossil propellants. For biomethane, landfill gas and anaerobic digestion of sewage sludge and of biological waste from households, businesses, and farms are likely to be too small sources to matter in this context. Instead, the main source of methane is likely to be gasification of waste and products from agriculture and forestry (see Figure 7).

Potential applications of biomethane for use in vehicles includes direct distribution to filling stations, use for production of electricity to electric vehicles, or use as feedstock in refineries for production of diesel and gasoline. The use of biomethane in electricity production is probably not realistic, because biomethane will not be able to compete with other electricity sources. Hence, to be used in vehicles, the methane should either be used in refineries or distributed directly to filling stations (Figure 7).

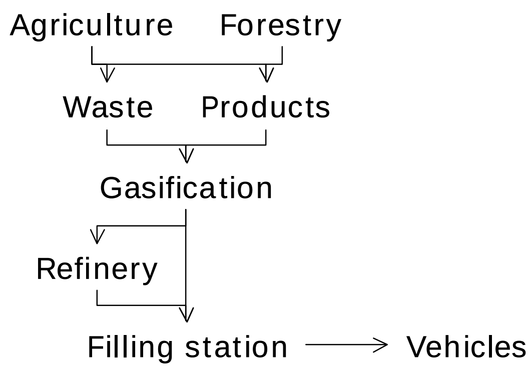


Figure 7: The object of study in the biomethane case

Figure 7 allows for eight different combinations of methane sources and methane applications. A more thorough pilot study might reduce the number of alternatives. The remaining alternatives can be compared in the LCSA as a basis for decisions of what alternative(s) should be selected or stimulated.

3.1.3 Sustainability aspects

A gross list of impacts is used as starting point for the selection of sustainability aspects. This gross list includes the environmental impacts of ISO-LCA, the social subcategories compiled by the UNEP/SETAC life-cycle initiative (Benoît and Mazijn, 2009), and a corresponding list of economic aspects. A brainstorm exercise is carried through to identify additional aspects that can be relevant for the decision at hand.

To be feasible, the LCSA should focus on a few sustainability aspects that are the most important to quantify. This means that they have to be important as basis for the decision, they have to be quantifiable, and there has to be a significant knowledge gap to fill through the LCSA. In the biofuel case, the most environmental impacts to analyse might be A) climate change and B) eutrophication. The most important economic aspects might be C) the life-cycle cost and D) the effect on global food prices. The most important social aspects in our case can be E) employment, and F) the national self-sufficiency in energy supply.

Referring to Figure 5, these aspects range from the product level (life-cycle cost) to the economy-wide level (employment).

3.1.4 Mechanisms

For modelling each of the selected sustainability aspects and of the technosystem, we need to identify mechanisms that can decide the outcome of the quantitative assessment. A new brainstorm exercise is carried through to identify mechanisms that can be relevant. Again, the LCSA has to focus on a few mechanisms. Hence, it is necessary to consider for each mechanism whether it is likely to be important for the results, if it is possible to quantify, and if there is a knowledge gap that a quantitative analysis can bridge.

Table 8 presents some mechanisms that are likely to be important to quantify in our case study. Some mechanisms are technical, e.g. modelling greenhouse gas (GHG) emissions from the technosystem and modelling emissions from the vehicles, etc. Other mechanisms are economic or social, e.g. the alternative use of biomass, economic impacts on global agriculture, etc. The impacts on total employment belong at the economy-wide level. The mechanisms are relevant for different objects of analysis (see Table 8), which implies that one could start modelling a relevant technosystem at a product-oriented level and replenish this with specific models for specific mechanisms for the meso-level and economy-wide level (see also Table 1).

Table 8: Mechanisms identified and selected for the different sustainability aspects.

Mechanisms	Product-oriented	Meso-level	E conomy-wide
Technical	A1./B1. Emissions from the technosystem B3. Effectiveness of techniques to reduce nutrient leakage C1. Total economic costs of the technosystem minus sunk costs		
Physical	-	-	-
Environmental	A4. Radiative forcing, atmospheric chemistry, and carbon sinks B4. Eutrophication impacts		A3. Carbon storage in soil and plants B2. Impacts of land use on eutrophication
Economic		A2 Alternative use of the biomass E1. Impacts on regional employment	D1. Impacts on global agriculture D2. Economic impacts on food prices E2. Impacts on total employment
Cultural, institutional, political		F1. Safety towards foreign trade policy pressure F2. Domestic energy supply at sudden blockade	F3. Refrain from imposing on energy resources of other countries

3.1.5 Methods and models

An adequate method for quantitative analysis has to be identified for each mechanism etc. This is a task for the LCSA practitioners rather than the stakeholders. However, it can still be part of the G&SD workshop with stakeholders to reduce the risk that the LCSA practitioners misinterpret the stakeholder inputs on the technosystem, sustainability aspects, and mechanisms. Making this step part of the G&SD workshop also allows for iterations, revising the selection of aspects and mechanisms.

The following methods and models can be useful to quantify the mechanisms and issues in Table 7:

A1&B1: collection of data on greenhouse gas and eutrophication emissions from the fuel life cycle (see Figure 7), but also from other parts of the technological system that are affected by the choice of fuel. Relevant subsystems to include in the expanded technosystem are identified by other models (see, e.g., A2 and B3 below).

A2: the alternative use of biomass can be analysed using a partial equilibrium model of the biomass and energy systems.

A3: to assess the impacts on carbon storage, it can be relevant to analyse how global land use is affected by the biofuel production. An adapted version of the economic computational general equilibrium (CGE) model Global Trade Analysis Project (GTAP) can possibly be used for this analysis (see Kløverpris et al., 2008). Soil models or data have to be added to quantify the implications for the climate.

A4: Climate change impact modelling using GWPs

B2: again, the adapted GTAP model can be relevant to analyse how the global land use is affected. Soil models or data have to be added to quantify the leakage of nutrients to water. Water models or data have to be added to implications for eutrophication.

B3: technological options to reduce nutrient leakage can be inventoried and assessed in a literature study.

B4: Eutrophication impact modelling using EPs

C1: the system cost can be quantified through an LCC. This study should take into account that some of the current infrastructure will remain in 2030. The investment costs for this infrastructure are sunk costs and should not be included in the LCC.

D1: the adapted GTAP model can be adequate to quantify how the global agricultural output is affected.

D2: a global partial equilibrium model of regional food markets might be adequate to quantify how an initial change in agricultural output affects food prices, the balance between supply and demand, and shifts between different types of food.

E1: regression analysis can be applied to quantify how the production of biofuel is likely to affect the rate of employment in rural regions of Sweden.

E2: regression analysis can also be applied to quantify effects on total employment in Sweden. A CGE model can be added to investigate how possible tax-funded subsidies and investments to the biofuel system can affect total employment.

F1: the marginal costs of domestic replacement of imported energy carriers can be investigated to quantify how the biofuel system affects the national robustness to foreign trade policy pressure.

F2: a dynamic model of the domestic self-sufficiency on energy can be developed to investigate how the biofuel system affects the national readiness to act at a trade blockade.

F3: a survey of published future energy scenarios is probably adequate to investigate and describe how the biofuel system affects the energy resources of other countries.

As with the sustainability aspects and mechanisms, the models applied range from the product level (e.g., LCC) to the economy-wide level (e.g., CGE models).

The study outlined in this section is very comprehensive: it would consist of more than a dozen different studies. Some of these studies might be rather small: literature surveys or simple applications of existing models. However, several studies require the development and/or use of rather complex combinations of methods and models.

In practice, the scope of an LCSA will have to be adapted to the resources available for the study. In most cases, the resources available would not allow for a study nearly as comprehensive as this, at least not with the currently available models and databases. Instead, a typical LCSA can include perhaps 1-3 sustainability aspects only, and 1-3 mechanisms and issues for each aspect.

Even so, the LCSA might benefit from establishing a network of experts that can carry through the analyses of the various mechanisms. No single person is likely to be qualified to apply all methods and models identified as relevant in the case study. This network should communicate during the analysis, since some of these analyses are interrelated. The system cost (C1) indicates the extent of economic stimulus etc. required to establish the system. If such stimulus is funded by tax-money, this might affect economic growth and, hence, total employment (E2). When planning the studies, it is important to consider what analyses will deliver results as input to other analyses.

When all separate analyses have been completed, a synthesis would be required to combine the results from all quantitative analyses with qualitative knowledge. These form the basis for overall conclusions and recommendations.

3.2 Example 2: waste management

This section describes the application of an approach that can be denoted LCSA in an ongoing research programme: Towards Sustainable Waste Management (TOSUWAMA; http://www.sustainablewaste.info/). This programme was initiated by the Swedish Environmental Protection Agency (EPA) to enhance the scientific basis for decisions aiming at a more sustainable waste management. The focus is on the upper levels of the waste hierarchy: waste prevention, preparations for reuse, and recycling of materials.

3.2.1 Question framing

The starting question in TOSUWAMA concerns the comparison of policy instruments and combinations of policy instruments for waste management. This question is clearly at the meso-level since it concerns the waste-management sector of Sweden. However, the policy instruments are likely to have effects far outside the Swedish waste-management. The environmental consequences of waste management often depend more on the impacts on surrounding energy, materials and nutrients systems than on the emissions from the waste management system itself (Ekvall, 1999). In addition, most policy instruments aiming at waste prevention have to be directed towards other parts of the society: households, industry, etc. For this reason, we can easily derive economy-wide questions concerning, e.g., the effects on the competitiveness of Swedish industry, economic growth and its related environmental impacts, employment, etc.

3.2.2 Objects of the study

The primary objects of study in this case are not technosystems but policy instruments. By the end of the year 2008, a list of 57 policy instruments was compiled in TOSUWAMA, ranging from fiscal instruments such as taxes as subsidies, to “soft” instruments including support for various cooperative solutions (Bisaillon et al., 2008). From this list, the most interesting policy instruments are currently being extracted for further analysis.

3.2.3 Sustainability aspects

When planning TOSUWAMA, the programme researchers defined a more sustainable waste management system to be a system that contributes to increasing efficiency in the use of natural resources, and to decreasing environmental burdens. Environmental improvements within Sweden should not be offset by unwanted consequences in other countries. To be sustainable, the waste management must also be affordable and widely accepted by the public as well as by key companies and organisations. Relevant environmental aspects are the environmental impacts of ISO-LCA. Important economic aspects are the cost of different waste-management systems, and the effect of different policy instruments on domestic economic growth. Acceptance is the only social aspect accounted for in this research programme.

Most of these aspects belong at the meso-level, but the effect on economic growth is an economy-wide aspect.

3.2.4 Mechanisms

The environmental impacts of different policy instruments will depend on, e.g., the quantity and mix of waste affected, the relative cost of different options for waste management, and the environmental impacts of these options. The quantity of waste, in turn, will depend on the economic activities in different sectors, and on the waste intensity of these sectors. The waste intensity will be affected by, e.g., technological development and environmental awareness. The environmental impacts of different options for waste management depends on what technological subsystems are affected, how the emissions and resource demand of these subsystems are affected, and how the environment is affected by the emissions.

A waste-management system is more likely to be accepted by the broad public if it appears reasonable and if it is easy to understand and participate in.

3.2.5 Methods and models

The environmental assessment is made through refining and combining a set of existing, quantitative methods and models (see Figure 8):

- the national waste statistics (SEPA, 2008), developed in accordance with the EU regulation on waste statistics (EU, 2002),
- the Environmental Medium term Economic model (EMEC), a CGE model of the Swedish economy (Östblom and Berg, 2006),
- NatWaste, a systems engineering model of the Swedish waste-management system (Ljunggren, 2000), and
- ISO-LCA of the different technological options for waste treatment.

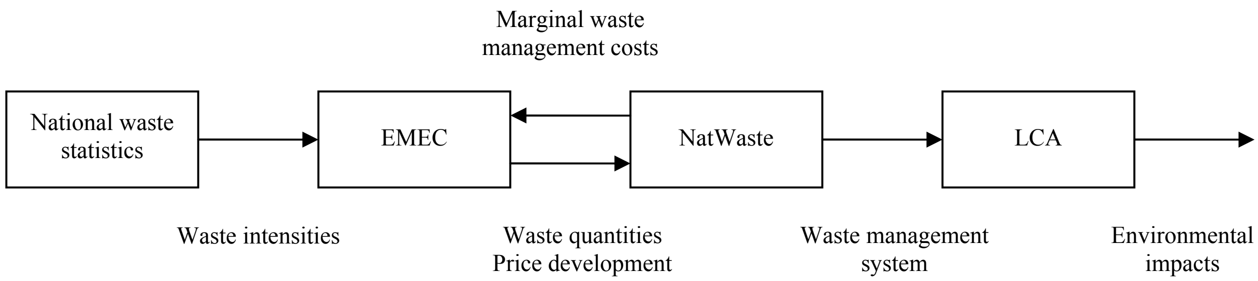


Figure 8: Combination of methods and models for assessing policy instruments for sustainable waste management.

The EMEC and NatWaste models will also give information on the relevant economic aspects. The combination of methods and models in Figure 8 will be applied to explore how the economy, the waste management system, and the environment might be affected in the year 2030 by the different policy instruments. The year 2030 is the time horizon because the CGE model is based on the current structure of the economy. Further into the future, the structure of the economy might be different, making the CGE model inadequate to describe the economy.

Looking no further than 2030, the uncertainties are still large concerning economic growth, technological development, environmental awareness etc. Scenario analysis is applied to deal with these large uncertainties: each policy instrument is assessed in five external scenarios with different assumptions regarding the future development of external aspects of politics, economy, technological development etc. (Dreborg and Tyskeng, 2008)

The public acceptance is not quantitatively modelled; however, the research programme includes anthropologists and environmental psychologists that investigate how people perceive waste, the waste-management system, and the information they receive on the waste-management system. This knowledge is gathered to be able to adapt source separation schemes etc. to the consumers.

To increase the likelihood of acceptance from key companies and organisations, a broad reference group was established with representatives from the waste-management sector, important industrial associations, an environmental NGO, etc. This reference group meet once a year to be informed about the progress of the research programme, and to give their feedback.

3.3 Example 3: diet changes

A third (real) example of LCSA is a recent project that was carried out on the impact of diet changes in the EU. The question was if a switch to a food pattern of the Mediterranean type will have positive environmental consequences. Such a diet is characterized by a partial shift from red meat to fish, poultry and more vegetables. As the environmental burden from agriculture, and especially from livestock breeding, is known to be quite important, such an analysis was interesting for policy purposes. The study has been reported by Tukker et al. (2009).

The study was in a number of senses a deepened and broadened LCA, deviating from the standard ISO-LCA. First of all, it was an IO-based LCA, with consumer activities included, so also different from "standard" EIO-LCA (Hendrickson et al., 2006). Next, it was based on the total consumption, not on an arbitrary functional unit. More fundamentally, it included the modelling of environmental mechanisms in so far, that a shift in expenditure to buying additional products through the savings on food expenditures was modelled. Finally, economic restructuring of the agricultural sector was also included with a partial equilibrium model (CAPRI; http://www.capri-model.org/). For instance, meat producers that face a decreased domestic demand may respond by increasing export, or by switching to alternative production structures.

In this example we thus see:

- the shift from the product level to the meso- (sector) or even economy-wide (nation) level;
- the inclusion of economic mechanisms at the meso- (sector) level;
- the inclusion of economic mechanisms at the micro- (private choices by consumers) level.

PART II

4 Inventory of present knowledge and data gaps

4.1 Purpose and method of analysis

This section inventories the research needs and gaps as resulted from the previous analysis carried out in CALCAS. This inventory is preliminary to the identification of research lines and exemplary research programmess which will be defined in final document D22 “Definition of research lines and exemplary research programmes for LCSA, incorporation in EU, national research programmes and academic curricula”.

Figure 9 represents the work method adopted for the inventory. Starting point is the LCSA framework, which includes both domains of empirical knowledge and normative positions (box 2), each of them covering specific mechanisms. The CALCAS project mainly focused on the *empirical domain*, analysing models in the domain of technical relations, physical relations, environmental mechanisms and economic mechanisms. Cultural, institutional & political relations have been addressed only to the extent covered by the case studies. Arrows show relations among methods and mechanisms (dotted lines represent weaker connections).

For the purposes of clarity and reducing complexities, empirical and normative domains have been kept separate in the phase of models analysis and alignment in the LCSA framework: nevertheless the case studies show how this distinction between normative and empirical domains is only a way to manage the complexity of the system, because actually a sharp separation is not possible, due to the strong interrelations.

The question addressed by the analysis is “*Where are the main gaps in the existing developments in LCA (box 1) and in the models potentially supporting life cycle analysis (box 3), in the context of the LCSA framework (box 2)?”* Input to the analysis is represented by the work previously done in CALCAS, and in particular by the following documents:

- D7 “Critical review of the current research needs and limitations related to ISO-LCA practice” (Box 1).
- D10 “Models and tools to consider” (Box 3).
- Identification of challenges and recommendations from a governance perspective, from D8 “LCA options for sustainable governance assessed”. The document analysed challenges for the further development of Life-Cycle Analysis (LCA) and other LCA-related tools from a governance perspective, considering their application context in policy and business and the linkages between policy and science (Box 4)
- Identification of needs and challenges from users’ perspective, from D9 “Demand for life approaches in sustainability decision support: user needs” It identifies decision-making situations, within four main stakeholder groups, where life cycle approaches is considered to play an important role as sustainability decision support (Box 5).

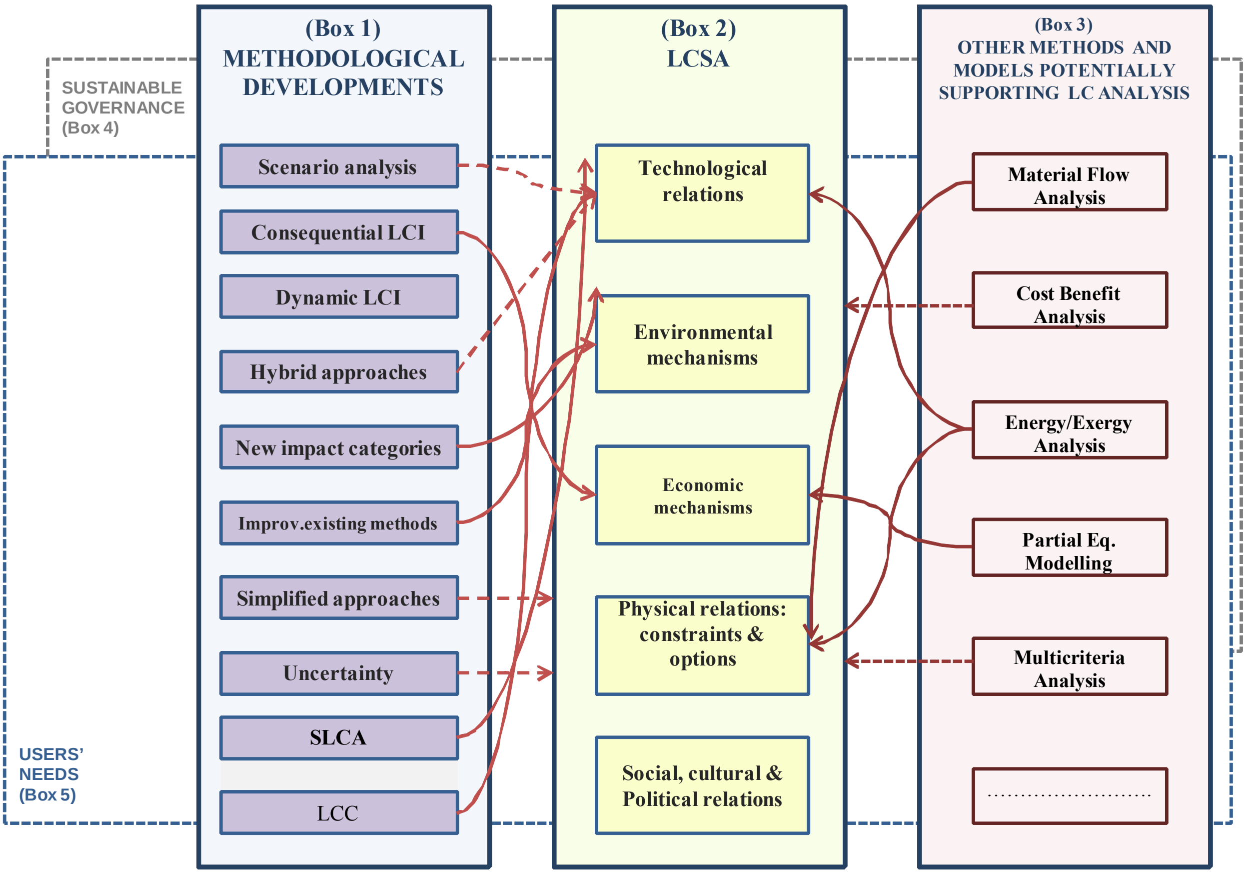


Figure 9 - Work method for the analysis of mechanisms and models in the LCSA framework

In addition, other sources have been considered:

- Report from the workshop on "Sustainability Assessment of Technologies (SAT)", held in Brussels 24-25 April and 14 June 2007
- Report from the CALCAS meeting with invited external experts on June 5, 2007 in Leiden
- Report from the CALCAS CALCAS-ESF Workshop "Life cycle analysis for sustainability governance. Designing transdisciplinary research lines for improved life cycle based systems analysis", held in Brussels 17-18 February 2009
- Handbook on Life Cycle Impact Assessment developed by EPLCA

The analyses of users' needs and of sustainable governance provided the terms of references for the definition of the LCSA framework. In particular, the work performed on governance (Vagt et al., 2008), from the view point of the institutional perspective, has contributed to better understand:

- what challenges arise from sustainability for assessment procedures and tools,
- what functions can be expected from current LCA to meet these challenges,
- a number of issues for broadening and deepening LCA to better meet the challenges of sustainability governance.

The users' needs analysis (Rydberg et al., 2008) provided a perspective for the identification and prioritisation of the scientific developments of sustainability decision making supporting methods and tools into specific research lines.

The other documents provided insights on the available knowledge, in particular they allowed for:

- The identification of the most promising approaches developed in the field of LCA (D7) which go in the direction of deepening the scope of mechanisms or the existing ones, and in the direction of broadening the scope of indicators and/or the object of the analysis. Besides, the document makes available also the analysis of these approaches in terms of perspectives of development, efforts required for their implementations and limitations.
- The analysis of other models than LCA which could potentially fit the LCSA framework (D10).

4.2 Main issues from review on ISO-LCA applications

The critical review of ISO-LCA (Zamagni et al., 2008) allowed exploring LCA in depth, highlighting a multitude of approaches and new thoughts. The developments identified can be classified in two main lines:

- Improvements of the most debated issues (system boundaries, allocation, data quality, uncertainty).
- Further developments of the methodology, towards an increased sophistication in modelling and a broadening of the scope of indicators, as to include also the economic and social perspective.

The improvements related to the ISO-LCA have been discussed in the deliverable D14 *Main R&D lines to improve reliability, significance and usability of the applications of standardised LCA*, while the further developments cited above are the focus of the analysis, and have been classified in terms of main topics of interest (i.e. the main elements, from the methodological viewpoint, that are dealt with in that specific phase). For each topic, two aspects have been summarised (Table 9):

- The most important issues discussed in literature, highlighting the core of the discussions and the (preliminary) answers given (column "issues").
- The main open questions that require further research on the topic (column "research needs").

Table 9 – Main issues from ISO-LCA

LCA PHASE and cross issues	TOPICS	ISSUES	RESEARCH NEEDS
GOAL AND SCOPE	**System boundaries**	**Reducing or eliminating the need for cut-off decisions** - Introduction of hybrid analysis - Development of process-based databases and default data to simplify data collection **Developing knowledge and methods to improve the basis for cut-off decisions** - Quantitative approaches to system boundary selection (e.g. Relative Mass-Energy-Economy) - Approaches to evaluate the significance of capital goods **Defining other types of system boundaries** - Geographical boundaries - Boundaries in time - Boundaries between the technological system and nature **Finding a more relevant system perspective than the cradle-to-grave perspective** - Consequential perspective (trace of the cause and effect chain originating the decision at hand) - Sustainability assessment perspective (no boundaries)	- No one method stands out but the consequential thinking opens new thoughts. Efforts in developing:: o more case studies o procedural guidelines.
	Scenario analysis	**Identification of main categories of scenarios (predictive, explorative, normative)** **Relevance, i.e. in which situation one approach is more suited than others**.	- Data o Availability of pre-defined scenarios, with a defined resolution at different level, as general input for many LCAs.
INVENTORY	**Consequential LCI**	**"Marginal" concept** - Identification of what type of marginal effects (short or long term) should be included in the consequential LCA - Identification of the marginal technology (e.g. five-steps procedure to identify long-term marginal technology developed by B. Weidema)	- Need of accumulated experience from successful LCAs and guidelines for application - Uncertainty related to the identification of marginal data and technologies - Identification of complex marginal effects (combination of short and long term marginal effects)

		Partial equilibrium modelling (PEM) - Use of PEM integrated into or used in parallel to LCA - Identification of goods for which a change in demand in a life cycle affect the demand in other life cycle - Identification of situations in which the use of PEM is relevant	- Data on price elasticities has to be estimated for many more products: they should be compiled in databases posted in connection to ordinary LCI db
		Experience curves - Use of experience curves for making forecasts of future emissions - Use of experience curves for estimating the effect of investments in new technologies - If the concept is integrated into LCA, what approach should be used in what circumstances - feasibility	- research needed on how transfer of knowledge and experience among technologies and geographical regions should be accounted for when applying experience curves - data: experience curves need to be established for more technologies: they should be compiled in databases posted in connection to ordinary LCI db
		Rebound effects - identification of several types of rebound effects - Methods to quantify them: own-price elasticity of demand, cross-price elasticity of demand, general equilibrium models, concept of marginal consumption. - Uncertainty and complexity	- It is considered methodologically immature - Identification of methods for quantifying them and evaluation of associated uncertainty is of paramount importance
	Time introduction in LCI modelling	**Dynamic LCA** - time as a continuous or discrete function - Understanding of what knowledge is added to LCA from dynamic models: indeed, depending on the situations, the use of recursive analysis in different time frames with data representing future technological relations could give a valid answer as well.	- Identification of the industry sectors where time-related issues are relevant to LCA results - Issue of distribution of impact over time - Efforts in developing technological scenarios for decisions related to the long period - Efforts in software and db development, as those available are based on static relations and are not supported by database that could be representative of the future situations.
	Hybrid approaches	**IO-based LCI** - Applications for analyses with a regional resolution - Advances in application for making process-based LCA more complete	- Data: reliability, availability and lack of consistency - Uncertainty factors for IO data - Inherent methodological shortcomings
		Physical input-output analysis - Limited and restrictive data availability - Lack of standardised methodology - Several methodological limitations	- The debate is still open on whether the benefits of using PIOT outweigh its disadvantages

		Integrated hybrid analysis - Methodological development already available - Application in the waste sector: Waste Input Output (WIO) Analysis - Opportunity for connecting analyses at micro and macro level	- Research efforts should focus on addressing the inherent methodological issues and subsequently developing well-structured input-output tables, with increased environmental data - Development of software tool that enables hybrid analysis - Need of accumulated experience from successful integrated hybrid analysis - Regarding WIO, further development of the model in the direction of including dynamics
	Allocation	**What the allocation problem is (when it arises)** **How the environmental burdens should be allocated** - System expansion stands out like the most suitable approach to allocation	- Efforts to reach a general agreement on which allocation approach is the most appropriate in different cases - To develop and agree upon a text clear and flexible enough to give adequate guidance on allocation in LCAs with different purposes
IMPACT ASSESSMENT	**Improvement of existing methods of characterisation**	**Identification of spatially differentiated characterisation factors for some impact categories** - Definition of the optimum level for the site-dependent factors - Discussion on which categories a spatial differentiation is necessary - Open questions about the comparability of the different models proposed and/or the possibility of extending the use of a model to other countries/regions	- Development of methodology for the definition of the optimal regions for site-dependent CFs - Identification of impact categories for which more detailed regional data are necessary - Availability of regional emissions and environmental data - Guidelines for practitioners and manageability-quality control of inventories
		Improvement of existing approaches for some impact categories, in particular human and eco toxicity, and resource depletion - Development of USEtox consensus model - Regarding resources, discussion moved from resource extraction to degraded form of the exploited resources - Proposed framework to quantify the effects of resource use, both biotic and abiotic	- Improvement of the consensus model - Improvement and further development ox existing methods, mainly PNEC and PA - For resources, further development of the proposed framework in terms of identification, for each resource, of values for functionality, quality indicators, ultimate quality limits, backup technologies.
		Further development of existing models to assess the damage - Currently focus on the development of damage models for ozone depletion and climate change - Need of expertise from other disciplines	- Evaluation of uncertainty of damage function - Development of a comprehensive methodology for endpoint approaches

	Development of mid-point and damage oriented methods in a common framework		- Provision of consistent and operational sets of methods and factors for LCIA - Uncertainty evaluation of damage function modelling
	Development of new characterisation methods and new impact categories	**RA in conjunction with LCA**	- Elaborations to identify which specific methods are useful to combine and for which decision-situations
		Noise	- Elaboration to other sources of noise than traffic - Discussion about aggregation of the traffic noise to noise from other phases of the life cycle
		Land use	- To build consensus on what needs to be assessed and then to elaborate indicators, characterisation methods and factors - To develop and elaborate methods with readily-available lists of intervention-characterisation factor combinations
		Exergy	- Development of general methodological guidelines in order to increase comparability among the different methods developed - Data availability
		Ionising radiation	- To expand the list of CFs to include more than the current 31 radio nuclides and 3 gamma radiating elements and radon - To get relevant emission data
		Water use	- Efforts in making operational the characterisation models and related characterisation factors
		Indoor and occupational exposure	- Emissions and associated characterisation factors - Trend: occupational exposure not as a separate impact category but a compartment in the human toxicity impact category, such as in the current improvement of the USE-tox model.
		Salinisation	- Due to the relevance in certain regions of the world, efforts in developing a list of CFs - Development of approaches also for other regions than South Africa and associated data collection guidelines

	Normalisation	Lack of emission data and/or characterisation factors in product and/or reference systems that could lead to biased normalisation	- To explore the possibility of merging the different works concerning normalisation factors on different spatial level, into one encompassing global normalisation data set, with regional differentiation. - Development of guidelines on how to deal with bias in normalisation
	Weighting	Several approaches have been developed: conjoint analysis, ecotax method, monetarization, etc.	- Controversies. No general strategies on weighting have been raised, but only individual improvements related to the single methods have been proposed.
INTERPRETATION	**Uncertainty analysis**	**Parameter uncertainty** **Model uncertainty** **Scenario uncertainty**	- Guidance on which specific techniques is better to use in which context - Methods to assess the appropriateness of distributions are necessary - A more detailed investigation of the understanding of parameters' interdependencies - Need of a framework helpful in organising the analysis and in identifying significant sources of uncertainties - Increased number of good practices
	Data quality assessment	No major new insights or progresses since the end of 1990's	- To work on reaching harmonisation and agreement among the methods already available
CROSS ISSUES	**Environmental Life Cycle Costing**	Conventional environmental LCC, WIO price model (hybrid LCC methodology), societal LCC	- Increased number of good practices for conventional env. LCC - Societal LCC still under development: it relation with SLCA should be further analysed
	Social Life Cycle Assessment		- Development of case studies - Formulation of indicators - Data
	Simplified LCA		- To reach consensus on when and how to simplify the analysis.

4.3 Main issues from the SWOT analysis

The SWOT analysis (Shepelmann et al., 2008) explored options for deepening and broadening LCA by reviewing and analysing various models. These models, whose application strongly depend on the field of application and on the users, their requirements and the goal and scope of the investigation, have been inventoried in order to analyse the opportunity to use them in the LCSA framework as a way to deepen and broaden the analysis. In particular, the following aspects have been investigated (Table 9):

- The level of application of the model, i.e. which kind of questions (product, meso, economy-wide) the model is more suitable for.
- The key points, i.e. elements characterising the model in terms of modelling principle, data needs, relations with other models, etc.
- Gaps and weak points, i.e. open questions that still reside, which could be translated into research needs.

The models have been classified in two groups: analytical models and procedural frameworks. The latter do not provide inputs for a better understanding of the mechanisms of the LCSA framework: indeed, as frameworks in their turns, they provide a place in which several analytical models can fit in a coherent way. From this view point they could be seen as alternative to the LCSA framework but with a narrower focus. Their contribution to the LCSA is related to the way in which the procedure is worked out, i.e. how the different models, both normative and analytical, have been put together in a coherent way.

Table 10 - Main issues from the SWOT analysis

	MODELS/APPROACHES	KEY POINTS	LEVEL OF APPLICATION	GAPS AND WEAK POINT
PROCEDURAL FRAMEWORK	**Environmental Impact Assessment (EIA)**	- It takes into account the time-related aspects, the specific local geographic situation and the existing background pressure on the environment - Participation of stakeholders - Process and documentation regulated in a EC directive	Micro	- Uncertainty, due to subjective evaluation of impacts - Rarely monitoring of actual impacts - High time and cost requirements
	Strategic Environmental Assessment (SEA)	- Focus on choosing pathways rather than determining the exact effects of different courses of action - Participation of stakeholders - It includes also social and economic dimensions in the environmental assessment	Macro	- Subjectivity: outcomes very much dependent on who is performing the SEA - Large uncertainties in data, knowledge gaps mixed with detailed data produced for specific purposes
	Sustainability Assessment (SA)	- Participation of stakeholders - It allows the combination of various tools	Micro, meso and macro	- Lack on guidance on what tools can be used - Integration of qualitative and quantitative information
	Ecodesign	- Facilitate supply chain integration - Reduce regulatory concerns - Integration of environmental issues at an early stage	Micro	- The tools used present different level of complexity: difficulties for SMES that do not have the necessary experience and resources.
	Sustainable Process Design	- LCA is used as a tool to assess the environmental sustainability - Integration of environmental and social issues at an early stage	Micro	- Little experience in applying SPD in practice - Interpretation of results can be difficult - The methodology is quite complex
	Product Oriented Environmental Management System (POEMS)	- Focus on the continuous improvements of products along the life cycle - Beyond the individual firm towards the product chain - Integration with existing certification systems (ISO 14001, EMAS)	Micro	- No standardisation - Outcomes may be affected by limited resources, lack of competencies by SMEs, unavailability of tolls tailored to industry needs

	MODELS/APPROACHES	KEY POINTS	LEVEL OF APPLICATION	GAPS AND WEAK POINT
	Multi-Criteria Decision Analysis (MCDA)	- Capacity to handle conflicting decision situations - Multi-disciplinary approach - Consideration of a large variety of criteria - Interactive learning procedure	Micro, meso and macro	- Representativeness of results could be questionable, as it is difficult to have a representative sample of stakeholders
ANALYTICAL METHODS & MODELS	**Material Flow Analysis (MFA)**	- Mass balancing principle - Accounting system - Info on the physical dimension of foreign trade - Direct connection to monetary assessment tools - Quite mature methodology - Data are publicly available	Macro	- The level of detail of input and output flows depend on the accounting categories - Efforts to improve the database for unused and indirect flows - Efforts to ensure the comparability of data sets across countries - Lack of waste data - Under representation of most damaging substances - Greater methodological standardization in the area of hidden flows - Efforts in the analysis of the correlations between different indicators
	Substance Flow Analysis (SFA)	- Mass balancing principle - Static and dynamic modelling, not a simple accounting - It can be used to assess potential constraints for resources and materials that are important for future technologies	Micro at the level of substances, macro at the level of economies	- It is limited to one substance (group) - Its scope is limited to those environmental issues that are directly related to the chosen group of substances - Dynamic modelling has high data needs and requires data and time consuming modelling - No formally standardised methodology
	Material Input Per unit of Service (MIPS)	- Focus on the use of natural resources - Input-oriented method	Micro	- Methodology not standardised - Limited data availability
	Energy/Exergy Analysis (EA)	- Scientific potential/strength in thermodynamic basis, entropy - Applicable to most situations and at all levels	Micro, meso and macro	- Risk of focusing too much on energy aspects and leaving out other important aspects -
	Environmental Extended Input-Output Analysis (EE-IOA)	- Computationally compatible with LCA and flexible at integrating other data sources - It is based on static accounting - Analysis of structural changes in	Mainly macro, it can be applied to meso level in some cases	- It assumes an identical production technology of imported products and the domestic economy, homogeneity and a single technology in the production process - EEIO tables at European level are still

MODELS/APPROACHES	KEY POINTS	LEVEL OF APPLICATION	GAPS AND WEAK POINT
	production and consumption patterns - Compatibility with macro-economic analyses and models		limited to few emissions to air - Level of disaggregation varies across countries - Old data
Hybrid LCA	For the EIO part see above + specificities of process-based LCA	Micro at the level of substances and products, meso at the level of businesses and sectors	See above
Risk Analysis (RA/ERA/HERA)	- It provides information concerning the timing of impacts - Site-specific impact modelling is feasible	Micro and meso	- It focuses on parts of the problem rather than the whole - The cost and time involved in obtaining data are huge - Multiple uncertainties
Life Cycle Optimisation	- It offers a set of alternative options for system improvements rather than a single optimum solution	Micro	- Methodology quite complex and requires know-how in both systems optimization and LCA - Time and resources, as it requires data on process and socio-economic aspects - Problems in non-linear optimization - Difficult interpretation of results
Carbon Footprint	- Data requirements limited to sources of GHG emissions only - Easy to calculate and to communicate	Micro, meso and macro	- Lack of consistency in methods for calculation and reporting - Tools currently available are either too simple or simplistic or too complex - Risk of unrealistic picture of the environmental impact as it focuses only on one impact category.
Life Cycle Activity Analysis (LCAA)	- It is based on the IOT format - It is a numerical technique, facilitated by the use of mathematical programming software - It incorporate techniques for representing environmental goals in the model - It takes into account both economical and environmental aspects in a coherent way	Micro	- It has LCA limitations when applied to situations other than micro-level products and services
Life Cycle Costing (LCC)	- Structure compatible with LCA - It adds an economic dimension to LCA	Micro	- Lack of standard - Efforts in developing case studies related to

	MODELS/APPROACHES	KEY POINTS	LEVEL OF APPLICATION	GAPS AND WEAK POINT
				the combined application of LCA and LCC - Difficulties in finding data representative of future markets and of their possible development.
	Cost Benefit Analysis (CBA)	- Comprehensive scope and effective aggregation of results into a single unit that can be easily communicated	Micro, meso and macro	- Credibility, related to the uncertainties of defining the costs and benefits of an option, and their monetary value - It requires expertise in both economics and natural science - Major involvement of stakeholders.
	Total Cost Accounting (TCA)	- It is capable of fully integrating a life cycle inventory of a product or process evaluation - It provides the economic counterpart of LCA - It pays specific attention to identifying hidden, less tangible and liability costs	Micro	- It gives only an in-depth analysis for one specific actor in the product chain, the producer - Difficulties in measuring intangible costs
	Total Cost of Ownership (TCO)	- It is a specific case of LCC, where the assessment takes the perspective of the product user/consumer - The supply chain covered by TCO is identical to the underlying life cycle of products and services.	Micro	- It is a narrow concept that only focuses on the product use/consumption phase of the product life cycle and does not always include end of life and waste removal costs - It pays no attention to business benefits other than cost savings - It is difficult to identify all costs
	ExternE	- It uses LCA in combination with impact pathway analysis and CBA - It provides a framework for transforming impacts expressed in different units into monetary values	Micro, meso and macro	- Still numerous scientific uncertainties about the dose-response functions for many impacts - The damage costs have not been quantified for all impact categories. The assessment of ecosystem impact is still preliminary -
	Eco-Efficiency (EE) Analysis	- Combined analysis of economic and ecological aspects without the use of monetarization or another form of converting these two aspects into one indicator	Micro at the level of substances and products, meso at the level of businesses and sectors	- Lack of an agreed method with appropriate tools
	Partial Equilibrium Models (PEM)	- It examines the conditions of equilibrium in an individual market or in part of a	Micro and meso level	- Large uncertainty in price elasticities estimate, demand curves and supply curves

	MODELS/APPROACHES	KEY POINTS	LEVEL OF APPLICATION	GAPS AND WEAK POINT
		national economy - It based on the concept of own-price elasticity of demand and supply - Use of PEM models in LCA in terms of exogenous variables		- A limited number of markets can be taken into account simultaneously
	Computable General Equilibrium Models (CGEM)	- They simulate how an economy might react to changes in policy, technology or other external factors - Methodologically robust - They often use the structure and data of national accounts (IOT) - They have been use in relation to LCA for identifying marginal effects of the studied changes	Macro	- Inherent shortcomings: market clearance, perfect competition, entirely price driven behavior of agents and perfect foresight - Data collection and modelling can be cost-intensive and time-consuming tasks - The time slice considered (usually annual) do not capture certain relevant effects that vary seasonally or hourly
	Social Life Cycle Assessment (SLCA)	- It adds a social dimension to LCA - Participation of stakeholders - It is based on the LCA structure	Micro	- Methodology not completely developed: weaknesses about modelling and data - Present software do not have features enabling SLCA

4.4 Main issues from other sources

Four other main sources have been used to inventory research needs and developments:

- *The ILCD Handbook*, in particular to the Guidance document for LCIA models, methods and factors (working draft):
  - Hauschild et al., 2008a. Recommended impact assessment methods for LCIA – Recommendations based on existing environmental impact assessment models and factors for LCIA.
  - Hauschild et al., 2008b. Requirements for environmental impact assessment methods, models and indicators for LCIA.

The documents provide a comprehensive framework for recommended methods and factors for LCIA, addressing environmental impacts at both midpoint and endpoint level in the impact pathway and covering different impact categories.

- *The CALCAS workshop with external experts*, held in Leiden on June 2007. The workshop aimed at widening the current LCA scope and findings by getting more inputs and new perspectives from experts outside the LCA domain.
- *The workshops on Sustainability Assessment of Technologies* (SAT), held in Brussels on 24-25 April and 14 June 2007. The workshop aimed at having a first discussion on the technical feasibility and on the methodological aspects of a possible SAT method based on a life cycle approach.
- *CALCAS-ESF Workshop* "Life cycle analysis for sustainability governance. Designing transdisciplinary research lines for improved life cycle based systems analysis", held in Brussels 17-18 February 2009.

ILCD Handbook – Guidance document for LCIA models, methods and factors.

In the ILCD Handbook main existing LCIA methodologies and additional models, which are not included in the selected LCIA methodologies, have been analysed for the part concerning the characterisation. The analysis was focussed on the overall principles, the consistency across impact categories and interesting innovative aspects. This analysis has led to a pre-selection of characterisation models, which have been analysed in the second stage of the project. The aim was to identify a method which can be recommended for each impact category including climate change, ozone depletion, human toxicity (including ionising radiation impacts), particulate matter/respiratory inorganics, photochemical ozone formation, acidification, eutrophication, ecotoxicity (including ionising radiation impacts), land use, resource depletion and a number of other impacts (noise, accidents, erosion, desiccation and salination). The most recent methodologies, especially the methodologies that combine midpoint and endpoint factors, like ReCiPe, Impact 2002+ and LIME obtained more attention in the evaluation (Hauschild et al., 2008 a-b).

The methods have been classified according to their quality into three classes:

- I: Recommended and satisfactory
- II: Recommended, some improvements needed
- III: Interim, i.e. the most appropriate among the existing approaches but immature for recommendations

Research needs have been identified for each of the impact categories, in particular where recommendations belong to Class II or Class III, and prioritised according to their importance for the characterisation modelling for the impact category.

Table 10 summarises the recommended methods and research needs that have stood out from the document.

CALCAS workshop with external experts, 5 June 2007, Leiden.

The discussion focussed on the scientific foundation of the framework, and pointed out the following main elements:

- ***Mass and energy balance***.
  It was considered a promising development path for broadening and deepening the analysis.
- ***Scenario analysis***.
  Suggestions came out on using scenario-inputs where possible and avoiding to model everything as that will make the analysis impracticable and the results diverging to all kinds of (opposite) directions with high uncertainties. The power of scenario analysis is rather to deal with diverging directions and related uncertainties.
- ***Functional Unit***.
  Which consequences for the functional unit in translating the analysis at higher levels? Key aspect is that the FU depends on the type of question, which can be formulated at product, meso and economy-wide level.
- ***Participatory approaches***.
  They produce soft information and that is their weakness, but they also show which information is left out of modelling approach, because it cannot be modelled. Thus, main suggestion was to combine participatory approaches with modelling of what can be modelled.
- ***Uncertainty***.
  The reduction of uncertainty in modelling should be the leading principle in elaborating the framework and making it operational.
- ***Data availability***
  Often the modelling is hampered by the lack of data. The issue of data requirements and handling is of fundamental importance to make the framework operational.
- ***Relation among LCA and other approaches***.
  It is open to further research how the methods of the framework should be used together. The hybrid LCA, further developed, has been suggested as a key approach to bridge the gap from product to meso/economy-wide level.
- ***Social aspects***
  The discussion on social aspects, only briefly mentioned during the workshop, highlighted several aspects that leave much room for research in the future: choice of sustainability targets and indicators; procedure (e.g. to include or not a participatory approach in the performance of a study); introduction of social mechanisms into LCA method as a physical relationships. The main suggestion was to start including social aspects as simply as possible, taking what is available, and see if that is sufficient for the moment and, if not, further build on that.

Table 11 - Recommended methods and research needs on Impact Assessment identified in the ILCD Handbook

	RECOMMENDED METHOD		**CONSISTENCY**	**RESEARCH NEEDS**
	MIDPOINT (MP)	**ENDPOINT (EP)**		
CLIMATE CHANGE	**IPCC** (GWP)- CLASS I	**RECIPE-** CLASS II	GOOD	High priority: - focus on EP methods (links between: Co2 eq and temperature increase; temperature increase and ecosystem and human health damages)
OZONE DEPLETION	**WMO** (ODP)- CLASS I	**RECIPE** -CLASS III	POOR	Short term research: - evaluate if it is desiderable to base the fate model on the sharply decreasing emission scenario; - Incorporate the damage to ecosystems. Further study of lime, which links also to crop loss, wood production and plankton loss, can help (first problem is the documentation of the method)
HUMAN TOXICITY	USEtox -CLASS II , III for certain factors affected by high uncertainty.	DALY calculation applied to USEtox MP- CLASS II/III	Can be assured	High priority: - indoor air quality and work environment; - metals (human exposure and effects); - pesticides, including residues in food chain Medium priority: - parameter uncertainty on USEtox CFs; more substances, user-friendliness of the model (only excel currently) Low priority: - dermal route of exposure for USEtox; - improvement of EP model for non-carcinogens (long term research)
PARTICULATE MATTER/RESPIRATORY INORGANICS	No recommended methods, but methods existing to calculate intake fraction are classified in CLASS I.	Adapted DALY calculation applied to USEtox MP- CLASS II	GOOD	High priority: - improve spatial differentiation on fate and exposure; - differentiate effect factors depending on the source and size distribution; - modelling effects factors to consider also surface and number instead of solely mass; - include NH3 emissions - evaluate whether chronic bronchitis adults is an important and which the severity

				factor is Medium priority: - consider the evolution of particle size distribution in modelling fate and exposure; - CF for particles <2.5 micron; - evaluate the use of the ECOSENSE model
IONIZING RADIATION	GARNIER-LAPLACE approach for ecosystems CLASS III; FRISCHKNECHT ET AL. 2000 method for human health CLASS II	Under the same assumptions as for ecotoxicity PDF calculation applied to MP is proposed for ecosystem CLASS III ; FRISCHKNECHT et al. 2000 method for human health CLASS II	GOOD	High priority: - ensure better compatibility of the model with USEtox for human and eco toxicity; - cover radon for indoor emissions Medium priority: - update the daly; - include the marine and terrestrial environment for the ecosystem damage; - extend the number of radionuclides; Low priority: - further develop endpoint models for ecosystems
PHOTOCHEMICAL OZONE FORMATION (POF)	RECIPE –CLASS II	RECIPE for human health - CLASS II; for impacts on vegetation, model may be built on EDIP2003 midpoint –CLASS II	GOOD FOR RECIPE	High priority: - impact on vegetation in recipe or development based on EDIP 2003; - consolidation of choices of models adopted; - CFs for CO and CH4; - comparison with respiratory inorganics xxx POF is of higher concern for vegetation Medium priority: - adaptation to other continents
ACIDIFICATION	Accumulated exceedence (POSCH) AE-CLASS II	None has sufficient scientific quality, but RECIPE is the most appropriate-CLASS III	POOR	High priority: - CFs for SO3, NO, NO2; - continental/regional CFs (Seppala method); - quantify uncertainties; Medium priority: - link between AE and endpoint; - waterborne emissions and CFs; - ocean acidification via CO2 immission; - investigation on neglecting deposition in areas below the critical load;

				- CFs HCl, CH3COOH, HCOOH
EUTROPHICATION TERRESTRIAL	Accumulated exceedence-CLASS II		Not Applicable	
EUTROPHICATION AQUATIC	RECIPE –CLASS II	RECIPE -CLASS III for freshwater, nothing for marine	GOOD for freshwater Not Applicable for the other	<u>High priority:</u> - damage model for freshwater for Europe; - damage model marine EU; - global midpoint model for aquatic EU; - develop an integrated model (terr, fresh and marine water) for regional and global scale; <u>Medium priority</u>: - quantity uncertainties
ECOTOXICITY	For freshwater ecotoxicity USEtox -CLASS II/ III (certain factors are affected by high uncertainty). None for marine and terrestrial ecotoxicity	USEtox BASED- CLASS III None for marine and terrestrial ecotoxicity.	GOOD	<u>High priority:</u> - international review on marine and terrestrial ecotoxicity; - metals bioavailability; - effects via food web chains; - inclusion of the internal critical body burden concept; - validation of model with field data (species diversity) <u>Medium priority</u>: - metabolites, substance coverage, uncertainties; - assess the relevancy of including the estuarine environment as compartment
LAND USE	Method of MILA' I CANALS CLASS IIII (it lacks completeness and applicability)	RECIPE- CLASS II	POOR	<u>High priority</u>: - extensive test of the MP method and CFs development; - for EP method: soil quality impacts, effects on climate change, regionalised CFs; - extensive test of RECIPE <u>Medium priority</u>: - uncertainty; - impacts on primary production; - more land use types; - integrate elements and data of other works (Swiss Ecoscarcity)

RESOURCE DEPLETION Inherent property of the material	EXERGY is to be preferred but not recommended		Not Applicable	Medium priority: - investigate if conceptual choices are acceptable
RESOURCE DEPLETION scarcity	EDIP97 update 2004-CLASS II CML2002	RECIPE-CLASS III	No consistency	Medium priority: - further development and integration of the two MP methods; - critical review and improvement of the EP method
RESOURCE DEPLETION water	SWISS ECOSCARCITY-CLASS II	NONE	Not Applicable	Medium priority: - refine the model
				High priority: - area of protection natural resources needs to be better investigated: which impacts does it cover? What is really important (stakeholder discussion)? - develop a model to assess biotic resources and species depletion both at MP and EP
NOISE	NONE	NONE		High priority: - develop a method for MP and EP categories
ACCIDENTS	NONE	NONE		Develop a method is of low priority
DESICCATION	NONE	NONE		High priority: - assess if it is possible to merge them under land use impacts
EROSION	NONE	NONE		
SALINATION	NONE	NONE		

The majority of these elements have been further elaborated and contributed to a better definition of the LCSA framework. Some of them pointed out also suggestions on the research path to run and specific research needs, and have thus been taken into consideration in the process of models alignment in the framework.

Workshops on Sustainability Assessment of Technologies (SAT), 24-25 April and 14 June 2007, Brussels.

The workshop discussed the main challenges in the area of Sustainability Assessment of Technologies, assuming as condition sine qua non that both the framework methodology and its derived methods and tools shall be based on a Life Cycle Thinking approach that takes into consideration all the three pillars of sustainability.

Main points raised during the discussion:

- ***FU***
  The concept of FU still applied also at higher level of the analysis that the product-oriented one. Main suggestion is that the scale of the FU should be so to represent the system level (e.g. the transport system of Europe), or sould be of the same size of the affected market.
- ***Rebound effect***
  They should be considered in the analysis as they have strong influence on the final results. Quantitative methods are difficult at present: the main suggestion for the present is to consider rebound effect in scenarios.
- ***Scenario-based approaches***
  The use of scenarios to tackle epistemological uncertainties is perceived to be particularly important in the field of technology assessment due to the unpredictability of the future development of the system under investigation in which the new technology is implemented. Scenarios were advocated to be necessary for both foreground and background systems. It was proposed that a number of reference background scenarios at 5-year intervals should be made available (e.g. in the ELCD database developed by JRC IES in Ispra), i.e. each process should be available in a number of scenario versions for each 5-year period.
- ***Input-Output Tables***
  Most of the experts were quite sceptical about both the current possibility to extensively use the input-output and hybrid approaches, due to the high level of aggregation25. However, it was recognised their importance in dealing with topics such as the assessment of different lifestyles and the effects of the globalisation on trade flows.
- ***Economic models***
  The dynamic modelling approach was identified as the most suitable for this kind of evaluation; nevertheless, from the methodological view point we are still far away from implementing such sophistication.
- ***Social dimension***
  It was stressed the importance of developing an approach to the evaluation of social aspects closed to the ISO 14040, an approach in which the participatory mechanisms should find a place.

CALCAS-ESF Workshop "Life cycle analysis for sustainability governance. Designing transdisciplinary research lines for improved life cycle based systems analysis", 17-18 February 2009, Brussels.

[25] The decomposition solution suggested by some participants was criticized as it would lead to a continuous re-adjustment of the whole matrix.

The workshop focussed on research lines for improved life cycle based analysis of products and their technology systems, for better sustainability governance. Main conclusions and suggestions were the following:

- ***Communication***
  The building up of a framework for sustainability analysis is important as well as the communication of results to policy makers. Efforts should be spent in understanding how to translate complex results in something that policy makers can understand.
- ***Short term research for improved LCA***
  What we need today are robust foundations from authoritative bodies and coherence, quality assurance, increased use/availability. The activities of the EPLCA are going in this direction, making available guidance documents for more sound applications, and encouraging the cooperation among the different stakeholders. Also the initiatives of UNEP-SEPAC contribute to strengthen the role of LCA, focussing on the topic of data availability (development of LCA databases in region in which they do not exist) and quality (access to transparent, free and good quality life cycle data).
- ***Procedure and modelling***
  Procedures are important as models. Indeed, there is no hard science solution for the sustainability assessment: we need a learning process, finding coherence rule among the different elements that make up the framework.
- ***Future***.
  In the sustainability framework, moving from micro to macro level, the long time frame becomes important and the issue of future states comes into question. Future is of relevance for all the main aspects, like technologies, markets, behavior, policies, impacts, uncertainties
- ***Broad questions***.
  A key challenge is represented by evaluations at macro level, like those related to e.g. new technologies (biofuels, nanotechnology), dematerialization & decarbonization, waste management & recycling, eco-innovation, emission trading system, etc.
- ***Micro vs. macro***, i.e. how to link sustainability decisions at micro level with consequences at macro level.
  Topics of relevance are those related to micro costs vs. macro growth, from functional unit to societal systems, upscaling, learning curves, resource constraints, role of IO vs. LCA.
- ***Meso vs. Macro.*** i.e. the proposed expansion of the United States biofuel targets (Meso) and implications on the global land use change (Macro).
- ***Data and models***.
  Several models have a specific place in the new LCA framework, and each requires specific data. The main challenge is to combine all this knowledge in a coherent framework, and efforts should be spent on analysing possible connections among the different methods and models: connection with IA & SEA, IO and CGE, incorporation of more mechanisms (rebound, markets, ...), broadening the spectrum of impacts (social, economic, but also environmental, e.g. regionalized), management of uncertainty and complexity.
- ***Role for decision-making***.
  Which is the role of LCA in the decision-making? Several suggestions arose during the workshop related to possible field of application, like analysis of micro (SME) vs. macro (EU), products vs. policies, retrospective vs. prospective, attributional vs. consequential, supply chain m*anagement, governance, benchmarking or planning*
- ***Standardization***, with reference to the framework, data, participatory approaches, legislation, directives, sustainability indicators.

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ANNEXES

Annex 1 CALCAS Project

CALCAS aims at identifying research lines on how to achieve a substantial efficacy increase in supporting sustainability (not only environmental) decisions, going beyond the shortcomings and limitations of current Life Cycle Assessment (LCA). Its general objective is to further develop the ISO-LCA[26] into a broader scientific framework, named Life Cycle Sustainability Analysis (LCSA) with the following features:

- improved reliability and usability of ISO-LCA;
- "deepening" of the present model (i.e. adding more mechanisms and/or more sophistications) to improve its applicability in different contexts while increasing its reliability and usability;
- "broadening" the LCA scope by better incorporating sustainability aspects and linking to neighbouring models, to improve their significance;
- "leaping forward" by a revision/enrichment of foundations, through the crossing with other disciplines for sustainability evaluation.

Partners of CALCAS are:

- Ente Nazionale per le Nuove Tecnologie, l'Energia e l'Ambiente (ENEA) Co-ordinator
- Institute of environmental sciences CML, Leiden University. Scientific Co-ordinator
- Swedish Environmental Research Institute (IVL)
- Wuppertal Institute for Climate, Environment and Energy
- Institute for Environment and Sustainability (JRC IES)
- School of Chemical Engineering Analytical Science – University of Manchester
- ARMINES
- Environmental Policy Research Centre (FFU) Frei Universitat Berlin
- Instituto Superior Tecnico, Technical University of Lisbon (IST)
- European Science Foundation (ESF)
- Institut für ökologische Wirtschaftsforschung gGmbH, (IÖW)
- Society of Environmental Toxicology and Chemistry - Europe VZW (SETAC EUROPE)
- Chemistry Innovation (CI)

CALCAS workprogramme has been developed along three main lines, producing a number of deliverables (see Table 12), available for downloading in the project informative web site www.calcasproject.net, or http://www.estis.net/sites/calcas/ :

[26] In CALCAS we adopted the convention to call ISO-LCA the Life Cycle Assessment as standardised by the ISO 14040 and 14044 norms

Table 12 – Work lines, main tasks and principles deliverables of CALCAS project

WORK LINE	MAIN TASKS	DELIVERABLES
Science framework	critical analysis of the present LCA scientific framework, in relation to the more general discipline of sustainability science and modelling	D1 Scope Paper; D15 A scientific framework for LCA
	detailed status of the art of LCA applications, with an identification of the most relevant development lines	D7 Critical review of the current research needs and limitations related to ISO-LCA practice
	SWOT analysis of the most promising tools and models for broadening and deepening LCA-methodologies	D10 SWOT analysis of LCA-supporting models and tools; D17 Options for deepening and broadening LCA
	a survey of existing training programmes characterised by life cycle thinking and identification of ways to promote and assist the incorporation of life cycle thinking in academic curricula and research; networking	D12 Training Implementation Plan on Life Cycle topics for Educational Organizations in Europe; D16 Strengthening European networks on Life Cycle topics – a CALCAS contribution
Analysis of user needs	Analysis of needs of four categories of users: Industry, Government, Consumers and NGOs, Research organisations	D9 Results from survey of demand for life cycle approaches in sustainability decision support: user needs; D11 Practical requirements for sustainability decision making. Summary Report of Workshop LCA and beyond – Science towards sustainability; D19 What LCA options may supply: user assessment
	LCA in relation with sustainability governance	D6 LCA options for sustainable governance assessed; D13 Sustainability governance with new LCA
Leaping forward: Crossing needs and science supply	Improvement of reliability and usability of ISO-LCA	D14 Main R&D lines to improve reliability, significance and usability of the applications of standardised LCA
	Deepening and broadening LCA	D18 Guidelines for application of deepened and broadened LCA
	Definition of new LCA strategies research lines and road map	D20 Blue Paper on Life Cycle Sustainability Analysis (The present document) D22 Research strategy for expanding Life Cycle Sustainability Analysis; (Later)

Annex 2: mechanisms for a full-fledged study on biofuels[27]

Do biofuels contribute to sustainability? The answer of course depends on the type of biofuel, on the biotic resources used, on the technologies employed to convert biomass into fuel, on the volumes and, from a different perspective, on the time scales to be considered and on the exact question(s) posed. On top of that, the answer also depends on the mechanisms modelled and the level of sophistication of modelling these mechanisms (two directions of deepening). The introduction of biofuels has been supported by LCA-type studies, not even explicit LCAs. They constitute the simplest type of models, and do not specify clear methods. Farrell et al (2006) have made a survey of US studies, reducing them to a common data format. These studies indicated a range of limited effects on CO_2 emissions, positive or negative depending on feedstock and the technology applied and, in a different perspective, depending on the background of the commissioner. Explicit LCA studies, with better defined methods, have led to similar outcomes; for a large review study, see Zah et al (2007). Next, a closer look at LCA methods shows that methodological choices, especially those regarding allocation methods, lead to differing and even contradictory outcomes, see Luo et al 2008a. Outcomes can also be greatly influenced by assumptions regarding emissions of N_2O, a potent greenhouse gas emitted from agriculture, diminishing the potential for climate change reductions in terms of only CO_2. The most positive LCA-type studies relate to second-generation biofuels, based on cellulosic feedstock, which cannot be used as food (except after biotic transformation, as into mushrooms like shiitake, or by ruminants, as into milk and meat). Technical assumptions about future technologies then may well lead to very attractive outcomes in terms of our technosphere relations with the broader environment. But will this future attractiveness be real? Simple LCA-type of studies up till now have not been adequate, so let us go through the various domains of empirical knowledge of Figure 2 and see what has been done and should be done.

Technical models are currently the subject of much analysis. These models guide technology development, seeking improvements on energy requirements in transport and biochemical transformation, and looking for biomass sources with the most favourable environmental profile. These models indicate that substantial improvements in environmental performance are possible. Cost indications are less clear. For some time to come, only residues from production processes, for instance in sugarcane mills, pulp industries and timber mills, may be profitable without subsidies. The outcome of this analysis is that we should go for second-generation biofuel, based on waste or low-price side products or for cellulose grown on poor soils with little fertiliser, preferably processed in flexible bio-refineries which can switch between inputs and can produce variable mixes of outputs. For the US, the choice then includes stover as a biofuel feedstock. This partly assumption-based theoretical analysis shows potentials which still remain to be realised in practice. Several studies have focused on this level, with links to land and water restrictions and markets (see Dornburg et al, 2008, for a highly comprehensive study). Kløverpris et al (2008) distinguish three approaches to land use. They describe the *LCA approach,* as developed in consequential LCA, which to some extent takes substitution mechanisms into account.

Physical models go into the physical constraints and options involved. Many new technologies, like solar cells, require rare metals whose production often cannot be easily increased. In the case of first generation bio-ethanol, however, this hardly seems to be the case. At the substance level, phosphate fertiliser may come to be in short supply, shorter than without biofuel. The intention for energy is to

[27] This is a much expanded version of this case as described in Huppes and Ishikawa (2009)

reduce dependence on fossil sources. As the effect will be very limited, there is no constraint here. The major constraint is in land available for production. The constraint is not a hard one, as land used for other purposes, especially wildlife areas, can be converted. This shift in land use due to market forces is taking place at a rapid pace, not only fuelled by energy policies and prices but also by rising food demand from an increasingly affluent global population, especially through growth in emerging countries like India and China.

Technically, we could grow all our food on a fraction of current land, with large tracts of land becoming available for biomass for energy, as IIASA studies have shown. The survey by Berndes et al. (2003) focuses on potential as well, but indicates the large uncertainties due to complex interrelations with other agricultural activities. In most instances, however, there are no mechanisms in society to shift economic activities towards environmentally attractive options. Two recent studies referred to above, Fargione et al (2008) and Searchinger et al (2008), have analysed the empirical land-use shifts resulting from biofuel production, decomposing several mechanisms involved. The environmental effects can be very substantial, whether directly or through their influence on production functions. The effects of clearing forests are especially large in the case of wet peaty soils, as in many places in South-East Asia. After the initial conversion, often based on burning with heavy emissions, large emissions will continue till the peat layer is fully oxidised. The contribution to climate change is enormous, negating any small positive effects analysed in step 2 for many decades if not centuries to come. Linking this partial dynamic analysis to an overall comparative-static framework is possible only by using some assumptions on how the effects will be dispersed in time, with some rules on attribution. If second-generation biofuel (here defined as based on transformation of lignocellulosis into fuel, possibly combined with producing other products) is a transitional phenomenon, to be taken over by algae, wind and wave power and solar cells, the climate cost of this transition are very much higher than when a long life for second-generation is envisaged. Though empirically disputed, this might occur due to the emissions resulting from for example transforming forest and grass lands to agricultural use, which somehow is to be attributed to the production of the biofuel for the period of production. Carbon storage back to the original levels might in principle take place thereafter.

In any case, taking this result into account leads to a ‘lose-lose’ situation, that is, the lower left-hand quadrant in figure 4. The eco-efficiency ratio is difficult to interpret in absolute terms, but the difference analysis with fossil can show the double negative score.

The land-use constraint can only be worked into the supply functions of all crops together, not specifically into those related to biofuel. The harder the constraint on land-use shifts, for example due to more effective land-use zoning laws, the more the increase in total biomass production will have to be gained on the given area, leading to more intense agriculture. This not only has direct effects on biodiversity in areas used for these other agricultural activities but also leads to increased emissions of N_2O, a potent greenhouse gas (GWP_{100} = 310). Even the more comprehensive studies being set up, like that by the Royal Society (2008), by the OECD (Doornbosch and Steenblik 2007), and by Dornburg et al (2008), do not mention this mechanism.

The *environmental models* relevant to the analysis could at first be the ones developed for LCA, linking environmental interventions of activities to *midpoints*, as intermediate environmental mechanisms, and then possibly to endpoints. For biomass and biofuel production, these include at least climate forcing or climate change, eutrophication, acidification, ecotoxicity and human toxicity. These and more direct mechanisms can be used to indicate the endpoints for evaluation, like biodiversity and more comprehensive environmental quality, human health and the more general life support functions of the environment. In the case of the conversion of wildlife areas to crop land, new environmental mechanisms were developed in the research papers by Fargione et al (2008), Campbell et al. 2008, Tilman et al 2006, Adler et al 2007, Gibbs et al 2008, Pineiro et al 2009 and Searchinger et al (2008), with more location-specific models. Such case-specific additions may be very useful in gaining new perspectives, but it is hard to establish rules about when and how to develop them. In this case, the huge Indonesian emissions (Indonesia being the world's third emitter of CO_2) give some indication of what to look for.

Economic models consider the main markets involved and how they will be influenced. What light can these models shed on the performance of bio-ethanol from corn? The 'main markets involved' is not a well defined category but offers considerable guidance. First, there are the market models of supply and demand in relation to the introduction of bio-ethanol. The first reasoned choice that has to be made is the choice of the volume of corn-based ethanol, in this case induced by policies, against operant market mechanisms which otherwise would lead to the fossil option. We assume the equivalent of 10% of the US gasoline market, which constitutes 40% of the global gasoline market. The first market involved is the food and fodder market for corn. Rising prices will shift demand to other staple foods and fodders, especially grains and soy, where prices will rise as well, as they already did aggressively with the much smaller amounts of corn now being used for ethanol. These are obvious markets. Next, however, there are more specific markets connected, which are not easily generalisable to broader classes of cases. In the bio-ethanol case, land markets are crucial, with environmental effects of land use changes a crucial factor in the eco-efficiency analysis, and crude oil markets. The increased demand induced by using corn for ethanol can be met in only two ways, by intensification and by area increases on formerly non-corn land. Increased supply will be based on both mechanisms. The environmental impacts have been studied with a focus on the conversion of land to agriculture in two Sciencexpress publications (Fargione et al 2008; Searchinger et al 2008). They decompose the forest clearing practices that are already occurring into a part due to increased food demand and a part due to fossil fuels; see "physical models" for the constraint aspect. They link the land-use change to carbon emissions due the one-off change-over. This dynamic effect is difficult to fit into a comparative-static model, as is required in the approach developed here, but should not be ignored for such a practical reason. It is clear that the major shifts in food prices will have substantial further economic, social and political consequences, as farmers in the world will get richer and consumers will be hit, especially poor ones in the larger cities of the developing world.

A second main area of market effects has been ignored altogether, viz. the effect on the fossil fuel markets. Adding a new source of fuel supply will lower fossil fuel prices, to the extent that the shift does indeed takes place. Supply will then be reduced, but it will not be fully replaced by the biofuel. The lower price, lower than what it otherwise would have been, will attract other demand. With a long-term price elasticity of demand around unity, a one percent price reduction will lead to a one percent increase in demand. The elasticity of supply is less accurately known. In the short term, supply is quite inelastic, so hardly any displacement would occur. In the longer run, however, supply is much more elastic and some displacement would take place. One market mechanism is that of land markets required for the increased volume of the total production of bio-energy, biomaterials and food. This land-use market is characterised by a physical constraint, the amount of land available on earth that is fit for production, when conditioning factors like climate and water availability are taken into account; see "physical models".

Other economic models cover the knowledge gained from general equilibrium models as have been developed especially for energy policy purposes. The EU's biofuels policy has been based on this level of analysis, incorporated in official impact assessments using economic models for the European energy market, PRIMES and GREEN-X; see CEC 2006 and 2007. They show substantial reductions in European emissions of climate gases, assuming the use of set-aside lands and not considering secondary effects. However, they are not technology-specific, do not take into account more comprehensive market mechanisms and do not cover physical limitations. Neither do they cover a broader set of environmental concerns. They do show, however, that there are economic and technical options for producing biomass for biofuel in Europe, whether attractive or not.

Cultural, institutional and political models is the least amenable to modelling. Empirical assessments may diverge widely. Optimists could paint a better future thanks to induced agricultural development, while pessimists may see a world breaking up as governments cannot meet the demands of the poor masses. While these considerations are clearly relevant, the point is how to narrow them down, preferably by reasoned expectations and otherwise by scenario assumptions. As with technology modelling, it is well possible to state conditions for sustainable use of biomass for energy, and frame them in scenarios. This approach has been followed in Dutch policy development. The Cramer Commission (2006), established by the current Dutch minister for the environment and responsible for implementation, specified indicators like 'Biomass production must not affect protected or vulnerable biodiversity and will, where possible, have to strengthen biodiversity.' (p III), with a certification system at origin to safeguard this. Such a certification system would inevitably ignore broader market mechanisms and other secondary mechanisms. Looking only at the mechanisms set in motion, not the adjoining policies, is difficult enough in itself. Developments like the nature conservation legislation now being introduced in Indonesia are triggered by disaster, but still: triggered. In the long run, such developments might be of prime importance. There is a clear gap in our ability to deal with these cultural, institutional and political mechanisms, not only in the case of biofuels.

One general concluding remark needs to be made on the outline for the relevant ideal full-case study. The large-scale policies to stimulate bio-ethanol in the US and Europe seem to have led to consequences which have hardly been covered in the preparatory studies till now. Studies could easily have investigated the additional demand for corn for ethanol, with land-use shifts towards large-scale corn production, and the reduced amounts of other staple foods produced as a result. The price rise in all staple grains is an easily quantifiable consequence, with poor populations in cities in developing countries suffering most, of course, and producers reaping profits. Also, such rising prices have induced large-scale development of tropical agriculture, not only for biomass-for-energy production but also for other products whose prices have risen. This expansion is more difficult to quantify but of course has led to serious loss of natural habitats and wet peaty soils, as in large parts of Borneo. Second- and third-generation biofuels, with different feedstocks, might have fewer negative effects, but this has not been investigated by analysing the mechanisms involved. The interesting question now is: why have we not foreseen such consequences of combined European and US policies, placed against a background of already rising prices due to growing populations and growing affluence, with increased demand for meat in China and other fast developing countries?
The simple answer seems to be that what is missing is a framework for such an analysis, not the will to make it. With hindsight, studies are now being undertaken to correct for some of the deficiencies in previous studies, taking into account the mechanisms which previous studies supporting biofuel policies had missed, by considering more complex effect mechanisms set in motion. To date, no study is available which covers all relevant mechanisms, let alone covering them in an integrated, quantified way. This seems a poor basis for a large-scale sustainability policy regarding biofuels, and bioenergy in general.

Annex 3: List of questions for public consultation

Please answer the following questions, providing as much details as you consider useful.

Send the comments and any enquire to: lca@enea.it or by fax to: +39 051 6098 675

Question 1
What do you think about the proposed LCSA framework and road map (see Figure 5)?
Suggested focus:

- mechanisms distinguished in LCSA modelling
- merging of inventory and impact assessment phases into one modelling step
- single modelling of the technosystem for the environmental, economic and social performance analysis

Question 2
About LCSA the Blue Paper proposes (1) to deepen the analysis to include more mechanisms, (2) to deepen particular mechanisms (e.g. better and spatially differentiated environmental modelling), (3) to broaden the analysis to include also economic and social indicators, and (4) to broaden the analysis from product-oriented to meso-level and economy wide LCSA. To achieve these developments, significant research is needed that will require prioritization. Which of the four lines above would get your research-priority? Please explain briefly why?

Question 3

Do you have any modification or additions to the inventoried research needs and gaps in Part II of this Blue Paper?

Question 4

What would be your personal top 3 of inventoried research needs and gaps in Part II (or added by you under question 3) to be addressed?

Any other comments

Annex 4: A short discussion of the received comments

The results of the open consulation have been processed in three ways:

- detailed comments have been incorporated in the specific chapter/section they referred to;
- Priorities and research needs identified by participants to the consultation have been included and considered in the final deliverable D22 "Definition of research lines and exemplary research programmes for Life Cycle Sustainability Analysis, incorporation in EU, national research programmes and academic curricula".
- General questions and feedbacks have been summarised in this Annex, according to the scheme adopted for the consultation.

The complete set of comments received during the open consultation is available for downloading on CALCAS web site .

Question 1
What do you think about the proposed LCSA framework and road map (see Figure 5)?
Suggested focus:

- mechanisms distinguished in LCSA modelling
- merging of inventory and impact assessment phases into one modelling step
- single modelling of the technosystem for the environmental, economic and social performance analysis

Mechanisms distinguished in LCSA modelling
- Generally the mechanisms distinguished in LCSA modelling are considered exhaustive.

LCSA framework and road map
- The figure 5 Road map for life-cycle sustainability analysis has been considered useful and innovative. Only minor modifications have been proposed: in particular one suggestion is to not indicate "Flow Diagram" as a separate modelling activity, because "Data, relationships between processes" involves also establishing the flow diagrams.

- Main objection to the LCSA framework refers to the proposed classification in three level of analysis (product-oriented, meso, economy-wide). One reviewer suggested to better differentiate the situations at least by kind of object (e.g. product, sector, Nation/person-average, policy) and level of analysis (micro, macro), effect on rest of economy (none, limited/marginal, structural) as well as kind of question (decision support, monitoring) to identify the right tool, method and data for each relevant combination. Indeed this was our intention as described at page 13. Anyway, this is a very relevant comment that requires a further discussion in the scientific community.

- The use of the word "evaluation" instead of "analysis" in LCSA has been suggested to underline that it includes also value judgements.

- A better explanation of the intended users of LCSA would also be appreciated.

Merging of inventory and impact assessment phases into one modelling step
- The text of section 2.1.4 has been modified to better clarify the proposal. There are diverging opinions on this aspect. Many agree with the proposal, while others are more sceptical, highlighting that keeping the two phases separate has the advantage of increased feasibility,

understanding and allows to use different and more adapted modelling techniques. Besides, there are suggestions to spend much more effort on the Inventory phase, as this is considered the key determining phase in LCA/LCSA. Anyway, this proposal refers to an opportunity for most complex situation where the merging of the two phases can provides more advantages. In short, the proposed approach should be further discussed, beyond CALCAS, to fully understand pros and cons.

- Some reviewers have stressed the need to show also in LCSA framework the required iterations among phases as the ISO 14044 framework does. Indeed, the iterative process is explicitly stated in page 28 describing the working method.

Single modelling of the technosystem

- Single modelling of the technosystem for the environmental, economic and social performance analysis is considered good, but it requires the development of robust indicators for environmental economic and social categories. In addition it has been stressed that LCA, LCC and SLCA have often different system boundaries: for example, in LCC R&D phase is included but it is normally neglected in LCA.

In general it is recognised that the "road map might serve as food for thought for more comprehensive considerations but is very extensive and with little support on what analyses to choose in specific situations" and "it will be a long way the fully operationalisation". Anyway, this latter aspect was outside the scope of CALCAS. See D22 for proposed research.

Question 2

About LCSA the Blue Paper proposes (1) to deepen the analysis to include more mechanisms, (2) to deepen particular mechanisms (e.g. better and spatially differentiated environmental modelling), (3) to broaden the analysis to include also economic and social indicators, and (4) to broaden the analysis from product-oriented to meso-level and economy wide LCSA. To achieve these developments, significant research is needed that will require prioritization. Which of the four lines above would get your research-priority? Please explain briefly why?

No clear consensus on priority among the proposed four lines emerged by the received answers One very relevant answer pointed out the need of combination among the four research lines. The proposed four lines have been also questioned as not fully justified in D20. This point will be fully addressed in D22. Additionally, the item 4 is connected with the proposed three levels of analysis (product, meso, economy-wide), and therefore questioned as described in Question 1 box above.

Question 3

Do you have any modification or additions to the inventoried research needs and gaps in Part II of this Blue Paper?

Received proposals are considered in D22. They are:

- Goal and scope: Data collection on typical systems boundaries associated with typical product oriented systems (attributional and consequential approach)
- Inventory-Consequential LCI: Procedural guidelines for the application of kuznet curve in the CALCAS methodology.

- Allocation, consequential modelling, system boundaries and data quality as well as documentation, review, and data availability as covered by ILCD handbook
- Research on the applicability and use of suggested methods in relation to existing business processes in companies: What are the role and potential of LCA and other analyses for sustainability in a wider business context?
- Research on the role and scope of action for sustainability measures for various actors in society (companies, policymakers, customers etc)
- The LCSA framework is mainly focused on assessing current (or expected) systems. A wider focus on how to induce change in e.g. technologies, behaviours and trends is missing.

Question 4

What would be your personal top 3 of inventoried research needs and gaps in Part II (or added by you under question 3) to be addressed?

The following priorities have been suggested:

- Uncertainty modelling, accuracy and scenario analysis guidance
- Data: Quality Assessment; LCI for developing countries; development of robust LCI dataset in the social and economic domain
- Environmental mechanisms: LCIA methods, especially on land use and similar, e.g. overfishing, spatial differentiation, better integration with EIA and RA; Improving/designing new methods of characterization to fit the necessities of the developing countries.
- Social LCA and social, cultural and political relations
- Economic mechanisms
- Normalization
- Consensus on when and how to simplify the analysis
- Applicability of suggested methods in relation to existing business contexts and scope of action for various business actors.
- “Future”, “micro vs. macro” and the “role for decision-making”.

Any other comments

Very relevant comments have been received on the boundaries between ISO-LCA and LCSA. How ISO-LCA is characterised in the document is considered inappropriate/too limited, because many things that are presented in CALCAS as "new LCA" are done already under and within ISO-LCA (e.g. substitution, consequential modelling, answering macro-level questions (e.g. IMPRO Cars and IMPRO buildings), etc.).
To answer these objections we can clarify that in the original CALCAS proposal New LCA was used as the term to indicate all developments in LCA that go beyond the boundaries of LCA as defined in the ISO 14040:2006 (E) and ISO 14044:2006 (E) Standards (abbreviated to ISO-LCA). The term “New LCA” was changed into Life Cycle Sustainability Analysis in the course of the CALCAS project, as this better indicated the contents of the developments and as the ‘shelf life’ of the term ‘new LCA’ was considered to be restricted. Within the CALCAS project we needed a reference for determining where LCSA starts. The published ISO standards, i.e. ISO 14040:2006 (E) and ISO 14044:2006 (E), constituted the most obvious reference for this.

By ISO-LCA we thus mean the written text of these two standards. It is explicitly not our intention to classify the ISO standards as static documents that will not be adapted anymore in future. On the contrary, we hope of course that they will be adapted particularly when some of the CALCAS research topics have matured and become daily LCA-practice. Moreover, issues for new LCA may already have been discussed in ISO TCs and there may have very good reasons not to adopt these issues within ISO for other reasons. LCSA is not in contradiction with ISO-LCA, but it builds on ISO-LCA extending its current boundaries to LCSA.
Other comments pointed out some lacks in the research gaps, in particular in relation to the needs of the developing countries. In this regards, research and development needs related to ISO-LCA are fully addressed by deliverable D14 and D18. These methodological questions have certainly a global scope, and thus should take into consideration also the needs of developing countries: nevertheless, we would like to underline that CALCAS has mainly a European scope as regard the effects of LCA applications.

One reviewer focussed all her comments on two questions: industrial “close loops” and the shift of the economy from products to product-service systems. The importance that LCSA can predict the impacts of these types of new solutions in the market was highlighted.