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D1 Scope Paper
Scope and Scientific Framework for the CALCAS Co-ordination Action

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Scope paper

Scope of and Scientific Framework for the CALCAS Co-ordination Action

Deliverable 1 of work Package 2 of the CALCAS project

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Executive summary

CALCAS is an EU 6th Framework Co-ordination Action for innovation in Life-Cycle Analysis for Sustainability. 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 Series of Standards (ISO-LCA), 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, is referred to in CALCAS as (new) LCA.

The general objective of CALCAS is to structure the array of LCA approaches and to develop ISO-LCA by:

- "deepening" the present models and tools to improve their applicability in different contexts while increasing their reliability and usability;
- "broadening" the LCA scope by better incorporating sustainability aspects and linking to neighbouring models, to improve their significance;
- "leaping forward" by a revision/enrichment of foundations, through the crossing with other disciplines for sustainability evaluation.

These objectives will be partly accomplished within the CALCAS project, as new practical strategies in LCA. For the other part, tasks will be formulated as research lines and as a road map, in terms of a number of research lines and a number of exemplary research programmes for sustainability decision support.

The report at hand here is deliverable D1 of work package 2 (WP2) of the CALCAS project. In D1 – called the scoping paper - the scope of the CALCAS project is determined and a scientific framework is drafted that will guide and align the work in all other WPs. This scoping paper determines in a more specific way what the CALCAS project will be about and what not. The scientific framework will be applied in WP3, 4, 5 and 6. The experiences gained with the scientific framework in WP 3-6 will be returned to WP2 that will then produce the final scientific framework based on these experiences as part of deliverable D15, scheduled in month 23.

Scope of CALCAS

In setting the scope of the CALCAS project boundaries need to be set for numerous issues. Below a point by point summary is presented of scope decisions on a selection of the main issues:

- Terminology. In several studies differing and overlapping terminologies with respect to the terms approach, method, model, tool etc. are used. In CALCAS the following terminology is adopted. The general term is Life Cycle Approaches, covering three levels: Life Cycle Concepts; Life Cycle Methods & Models (including ISO-LCA and (new) LCA); and Life Cycle Tools, including software and databases.
- Life cycle based. The focus of CALCAS is on life cycle approaches only. Other types of methods will only be taken into account if relevant for life cycle based analysis. The prime focus is on the environmental pillar, with due consideration to the economic and – to a lesser extent –the social dimension of sustainability. The environmental aspects covered are placed

systematically in causal chains linking the system of economic activities (the *inventory analysis* in ISO-LCA terms*)* to ultimate sustainability values. Economic aspects are covered both from a collective, a governmental and a private perspective. Social aspects are more in a stage of conceptual development. CALCAS will contribute to that development, by indicating which aspects can be covered now in different life cycle approaches, and which cannot.

- Demand driven. The demand for life cycle based sustainability information guides the supply, not the other way around.
- Governance. With respect to governance, the scope of CALCAS covers all types of governance, at all levels of decision making, and for all questions arising there. The focus is thus more on clarifying these complex relations than on filling in one part as a detail.
- Evaluation. Evaluation, though essentially subjective and value based, is a central element in practical decision support, both at a strategic and at an operational level. Clarifying the main structure of what can be evaluated is part of CALCAS.
- Future oriented. With respect to questions posed, prime focus is on future oriented questions as opposed to questions on past performance, and on synchronical comparison between future states as opposed to diachronical analysis (comparing states before and after).
- Decision makers. CALCAS aims to cover all types of decision makers.
- Europe focused. CALCAS will focus on life cycle analysis requirements for Europe and similarly industrialised countries, while actively investigating how demand from developing countries differs and might be incorporated in the life cycle approaches investigated.
- Drivers and barriers. The subject of creating drivers for using sustainability information, such as developing proposals for regulatory activities, mainly lies outside the scope of CALCAS, rather belonging to the domain of policy oriented analysis. Barriers to the use of sustainability information partly are of this policy nature as well. CALCAS intends to point at some drivers and barriers but it is beyond the project's scope to elaborate them.
- Broadening LCA. Steps towards including more types of sustainability aspects will be investigated actively and in depth.
- Deepening LCA. The steps towards including more mechanisms and detail will first search for options in depth while staying within the realm of steady state or comparative static equilibrium analysis as central modelling mechanism. Steps towards endogenising more mechanisms in LCA, going beyond the integrative platform of steady state analysis, will primarily be investigated at a conceptual level only, to see what might become possible.
- Build on UNEP-SETAC work. Both for deepening and broadening LCA, results from the working groups of the UNEP-SETAC life cycle initiative will be an important input.
- No emphasis on tools. Development of software and data bases is not part of CALCAS, nor is the survey of what is available. Indicating requirements on the development of these tools, especially if methods aspects require further research activities, exploring options for making information from other domains available for life cycle analysis is part of CALCAS.
- Emphasis on methods and models. Key scoping point of CALCAS is to clarify the options and structure for demand and supply of information, and to indicate how most relevant operational models may be developed for actual decision support.
- Implications for work plan. All scope decisions taken in this scope paper give guidance to the detailing of work plans of all WPs, will be implemented by the WP leaders and may have consequences for the specification of their deliverables and planning of activities.

Scientific Framework

The scientific framework presented as part of this scoping paper is supposed to be the implicit basis of all models of sustainability analysis that address the interaction between economic systems and environmental systems. The framework is developed on the basis of a discussion of theoretical considerations and experiences with a number of concrete models. As part of the development of the framework, the following topics are discussed subsequently:

- Structure. What is the overall structure of the relation between the economy and the environment, and how models may be used to understand this relationship? A general overview of considerations is given, amongst others introducing the IPAT (Impact, Population, Affluence and Technology) equation and the DPSIR (Drivers, Pressures, State, Impact, Responses) framework and broadening the discussion to economic and social aspects. Important structural aspects of models include the distinction between a system and its environment; the internal structure of a system in terms of its components; the relationship between the components; and the relationship between the system and its environment. Various models, often using ISO-LCA as the prime example, are discussed to illustrate the various structural aspects.
- Mechanisms. How do models address some basic mechanisms that can be of interest? Models that model the relation between economic activities, such as production and consumption, and the environment, invariably contain information on economic mechanisms. This can be done at various levels of sophistication, and in various ways.
- Time and space. How do models treat time and space? In general, activities, emissions, impact and other events happen at a specific place and at a specific time. All models that somehow deal with more than one activity, emission, impact, etc. thus have to consider how to treat differences in place and time. Different options for handling time and space in modelling are discussed.
- Linking. What are the different options to link two or more models? Two fundamentally different approaches to linking models are distinguished. Soft linking means that the results from one model are manually fed into the other. Hard linking means that the models are integrated to become, in essence, a single computer model.
- Simplification. Which main strategies in simplifying ISO-LCA are conceivable for the two major phases of LCA: inventory analysis and impact assessment?

Based on these reflections and considerations a scientific framework has been drafted and a selected number of concrete methods and models has been categorized with this scientific framework, for example the ISO-LCA model. The categorization of other methods and models to this scientific framework will take place as part of WP3 and WP5, and will be reported in the same format. Experiences gained while applying the framework in WP3 and WP5 may lead to adjustments of the framework, which will be taken into account in D15.

Finally, some practical aspects are explored. All models require data, and some of these data may be common to several models. Some possible practical data consequences of broadened and deepened LCA are briefly discussed.

1 Introduction

LCA approaches have matured over the last decades and become part of the broader field of sustainability assessment. As defined in ISO 14040 (Anonymous, 2006a) and 14044 (Anonymous, 2006b), LCA is a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle". LCA as standardized by ISO (hereafter abbreviated to ISO-LCA) has been the driving power for this LCA diffusion.

The increase of its use in applications has been continuous, but not as widespread as expected. The EC has conducted some studies (e.g., Ernst & Young, 2000; Ansems et al., 2005) about the reasons for that and it has defined a strategy for a faster penetration. The main identified problems are: the limited availability and the easy access to data, the data exchange, simplified procedures and software tools especially for SMEs. In this context, the Directorate General Joint Research Centre and Environment coordinates the European Platform on Life Cycle Assessment to develop reference data and recommended methods for more reliable LCA studies from a European perspective, for supporting improved environmental performance and competitiveness (http://lca.jrc.ec.europa.eu/).

Moreover, the ISO-elaboration of LCA has often been considered to be too restrictive and there is no common agreement on many of the underlying details, as on system boundaries and allocation methods (Ekvall & Finnveden, 2001; Ekvall & Weidema, 2004; Guinée et al., 2004; Huppes, 1993; Lenzen, 2001; Miller & Theis, 2006; Suh et al., 2004, Tillman et al., 1994), discussions on "dynamic LCA" (Kendall, 2004; Pehnt, 2006; Björk & Rasmuson, 2002; Masini & Frankl, 1997; Hirao, 1999), "spatially differentiated LCA" (Tolle, 1997; Moriguchi & Terazono,.2000; Nigge, 2001a; Nigge, 2001b; Bellekom et al., 2006), "risk-based LCA" (Assies, 1998, Nishioka et al., 2006; Saouter & Feijtel, 2000; Sonneman et al., 2004), and other terms that display a clear deviation from the basic principles of the ISO elaboration of LCA.

From these and also other references (e.g., Weidema, 1993; Azapagic & Clift, 1999; Weidema et al., 1999; Hauschild & Wenzel, 1998; Ekvall, 2000; Guinée et al., 2002; Mattsson et al. 2003; Weidema, 2003) it becomes clear that there is a need for structuring this varying field of LCA approaches while taking into account more types of externalities (economic and social costs) and more mechanisms (rebound, behaviour, price effects), handling time ((quasi-)dynamic, steady-state) and space differently (spatially differentiated or spatially independent) and/or meeting specific user needs such as in simplified LCA, thus increasing the efficacy of sustainability decision making.

CALCAS is an EU 6th Framework Co-ordination Action for innovation in Life-Cycle Analysis for Sustainability, aiming to achieve this efficacy increase. CALCAS will go beyond the boundaries of ISO-LCA. Going beyond ISO-LCA, might be called Life Cycle Analysis approaches, as is done in the 4th Call of FP6. However, both Life Cycle Assessment and Life Cycle Analysis are abbreviated to LCA. Therefore, within the CALCAS project we will refer to (new) LCA, a result of innovation, in contrast to ISO-LCA.

The general objective of CALCAS is to develop ISO-LCA by:

- “deepening” the present models and tools to improve their applicability in different contexts while increasing their reliability and usability
- “broadening” the LCA scope by better incorporating sustainability aspects and linking to neighbouring models, to improve their significance
- “leaping forward” by a revision/enrichment of foundations, through the crossing with other disciplines for sustainability evaluation.

Specific goals or tasks to mend main deficiencies and limitations as indicated are:

- to derive specific models and tools for specific decision situations, including also new applications as for instance in prospective technology assessment;
- to link social mechanisms to technical and physical relations;
- to link micro level choices to macro level sustainability requirements, involving not only environmental but also economic and social sustainability aspects;
- to build a common framework for sustainability evaluation;
- to link the development of informational tools to the newly emerging modes of governance.

These tasks will be partly accomplished within the CALCAS project, as new practical strategies in LCA. For the other part, tasks will be formulated as research lines and as a road map, in terms of a number of research lines and a number of exemplary research programmes for sustainability decision support. The strategy and road map developed is input in public and private research programmes, in academic curricula, and in R&D programmes in industry.

The report at hand here is deliverable D1 of work package 2 (WP2) of the CALCAS project. In D1 – called the scoping paper - the scope of the CALCAS project is determined and a scientific framework is drafted that will guide and align the work in all other WPs. This scoping paper is a key deliverable of WP2, but also for the CALCAS project as a whole, as it determines in a more specific way what the CALCAS project will be about and what not. The scientific framework will be applied in WP3, 4, 5 and 6. The experiences gained with the scientific framework in WP 3-6 will be returned to WP2 that will then produce the final scientific framework based on these experiences. **Figure 1** summarizes the relations between D1 and other deliverables and WPs of the CALCAS project.

In order to understand the coherence of the CALCAS project, the overall structure of the CALCAS project is briefly drafted in Section 1.1. The goals of WP2, of which D1 is part of, are discussed in Section 1.2. Finally, Section 1.3 provides a reading guide is given for the remainder of D1.

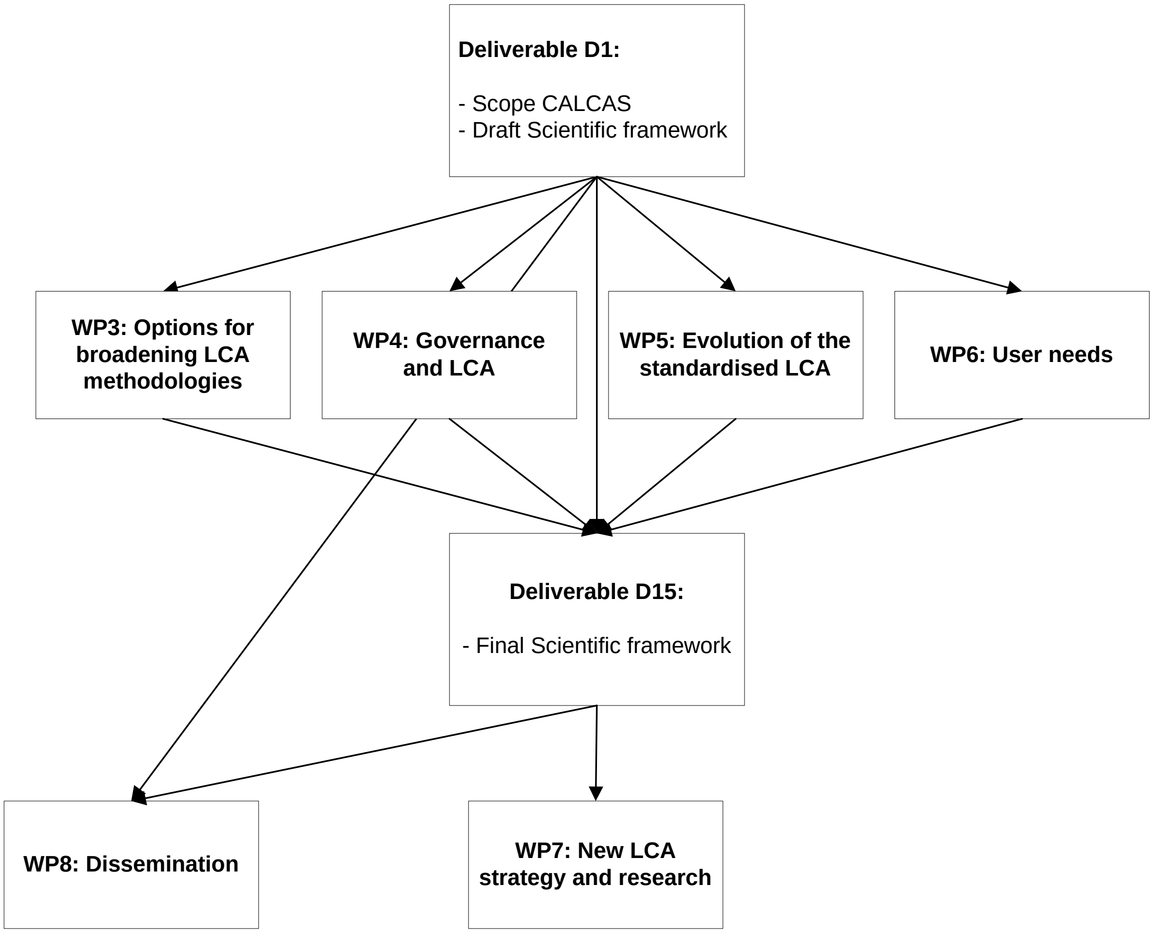


Figure 1: Relations of WP2 deliverables with other WPs.

1.1 Overall structure of CALCAS

In addition to the overall project co-ordination line 1 (WP1) and the dissemination line (WP8) that speak for themselves, the CALCAS project is structured along three main activity lines:

1. sustainability science supply: the specification of available knowledge, gaps therein and strategies for filling these gaps;
2. sustainability science demand: the specification of aligned knowledge requirements for public organizations; industry and industrial organizations; consumers, citizens and NGOs; R&D sector, reckoning with several levels of decision making, from decisions on purchasing and installation maintenance to policy strategies and R&D strategies in firms, systematically placed in the new governance perspective;
3. linking supply and demand: the specification of a main sustainability research strategy and research lines and programmes for focused scientific development.

The first activity line in the project is the specification and ordering of the sustainability science supply, embracing WP2, WP3, WP4 and WP5.

WP2 is entitled "Scope definition: framework for LCA science supply and demand". Its main objectives are to define:

- the scope of the project, in terms of broadness of LCA expansions to consider;
- a scientific framework for the program, guiding and aligning the work in all other WPs.

WP3 is entitled "Options for broadening LCA methodologies". Its main objective is to explore options for broadening LCA methodologies beyond the current ISO framework, e.g., by incorporating (parts of) other models and tools; by indicating combinations with other models and tools; etc. A simple case study will be developed to illustrate the practical application of some of these models. This case study will be designed with the aim to demonstrate how various models are typically used in various areas of a study, and give insight on different aspects respectively.

WP4 is entitled "LCA and institutions for governance: Position survey". Its main objectives concern analyses of actual and potential relationships of LCA and governance:

1) analyses and implications of input of policies and institutions for the construction of LCA and of normative inputs for LCA deriving from political goal-setting which are expressed often explicitly and sometimes also implicitly in strategies and also instrumental approaches;
2) elaboration of a systematic overview of alternating influences between pressures from persistent environmental problems and their uptake by LCA;
3) analysis of the use of LCA as a knowledge base for sustainable governance.

WP5 is entitled "Deepening and broadening of the standardised LCA". Its main objectives concern the identification of scientific trends and action lines, building on the current state-of-the-art, to improve reliability, significance and usability of the applications of standardised/ISO-LCA.

A second activity line in the project is the specification of demand for life cycle analysis for sustainability, which is organised in one work package: WP6.
WP6 is entitled "Demand for science in sustainability decision support: user needs". Its main objective concerns the identification of presently partially met needs and of future needs by:

- public authorities;
- business (industry, retailers);
- NGOs, consumer associations, citizens;
- R&D programmers (European Technology Platforms, National funding organisations).

The third activity line of the project is the innovative integration of supply and demand, focused at cross-linking the two at a higher level, through innovative research and development analysis of models and tools for sustainability decision support. This is organised in one work package (WP7), which is entitled "Definition of new LCA strategies research lines and road map". Its objectives are to:

- specify new LCA strategies as practically as is possible and, corresponding to the LCA advances identified in the other WPs,
- to develop overall research lines and a roadmap for their further development, with exemplary research programmes.

The CALCAS project structure is briefly summarized in Figure 2.

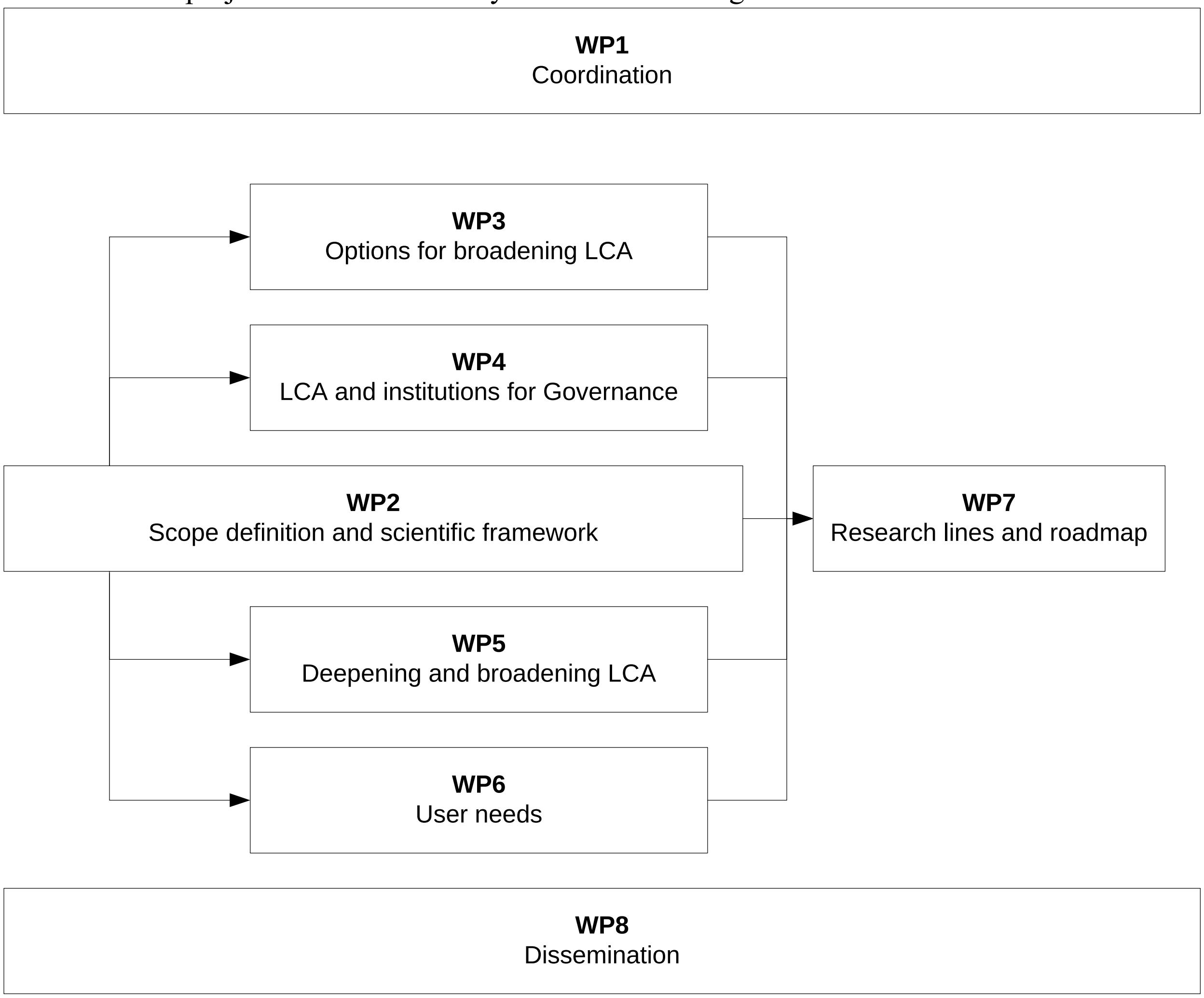


Figure 2: Overall structure of the CALCAS project.

1.2 Objectives of WP2

The objectives of Work Package 2 (WP2) are described in the CALCAS proposal as follows:

- To define the *scope* of the project, in terms of broadness of LCA expansions to consider.
- To define a *scientific framework* for the program, guiding and aligning the work in all other WPs, by creating
  a) a common vision for the main theoretical and practical aspects of the two fields (supply and demand), to be investigated and the specific objectives to be reached;
  b) the internal subdivisions of each of the two fields (supply and demand), the starting position, the boundaries and the overlapping areas among WP3, WP4, WP5, WP6 and consequently the whole interrelations system;
  c) the related work program (modalities, models and methods, deadlines, etc).

Two parts are thus to be distinguished: scope and scientific framework. Building on the CALCAS proposal, WP2 needs to further specify the *scope* of the whole CALCAS project in terms of,

- demand for life cycle based sustainability decision support for different decision makers in different decision situations;
- the options to supply this life cycle based information, specifically indicating the LCA expansions to consider;
- boundaries, structure and the mutual relations of the other work packages-in-content, WP3, WP4, WP5 and WP6.

The *scientific framework* is intended to clarify

- the definition and boundaries of ISO-LCA and broader (new) LCA;
- life cycle based methods and models and adjoining methods and models for environmental sustainability analysis: how do they relate, what type of questions do they address and what is their complementary value?

The framework should serve two derived purposes:

1. to help clarify the state of the art; and
2. to indicate directions for better and scientifically more aligned model development, as in terms of time treatment, location specification, empirical mechanisms involved and structure of evaluation to more firmly establish the scientific foundations of life cycle analysis.

Various modes of LCA will be identified and their scientific foundations unravelled. An inventory of existing life cycle based and other methods and models for environmental sustainability analysis will be made using available literature in this area. Methods and models will be characterized as to their handling of time, space, empirical mechanisms (endogenous or exogenous), and with their relation to decision support, involving methods of evaluation including multi-criteria analysis, trade-offs, and weighting procedures, both between environmental aspects and between environmental, economic and social aspects.

The WP2 objectives are reached through two deliverables:

- D1, Final Scope paper (month 6): A scoping document, first draft in month 2, providing framework, scientific foundations and definitions, which serves as an input for WP3, WP4, WP5 and WP6 (month 6). A journal summary of the main achievements will be also published for broad dissemination and peer review.
- D15, Final Scientific Framework report. (month 23): Report on scientific framework and modes of analysis, draft as input to the other WPs and the final version based on inputs from WP3, WP4, WP5 and WP6, including their final reports (month 23).

1.3 Reading guide

The work in WP2 will be along two lines:

- the scope definition, as on what will be included and what not, and the level of ambition
- the scientific framework, to keep the discussions precise and focused and to specify results in content and research programmes in an unambiguous way.

Chapter 2 will focus on scope issues, discussing the three pillars of sustainability (People, Planet and Prosperity (EC, 2002), the demand of sustainability knowledge in terms of questions to be answered, decision-makers, decision situations, and the supply of sustainability knowledge in terms of concepts, methods and models and practical tools and data, and ultimately linking demand to supply, the scope of CALCAS will de derived and summarized.

Chapter 3 focuses on developing a theoretical scientific framework theoretically analyzing interactions between the economy and the environment, general modelling principles, issues of economic mechanisms, issues of environmental pathways and impacts and issues of time and space.

Chapter 4 inventories existing methods and models and classifies a selected number of these, including ISO-LCA, to the theoretical framework as developed in Chapter 3.

Finally, Chapter 5 discusses practical issues related to data (e.g., which data are available and which are missing), format and software (e.g., how do current data formats and software fit into the framework and what is missing).

2 Scope of the CALCAS project

2.1 Introduction

In life cycle based analysis for sustainability, demand for information assessing various sustainability options is central. From high level strategy choices to detailed technology and product choices, the analysis is to give insight in mechanisms and to give insight in relevant effects. The ultimate question always is how decisions can move society towards sustainability and derived from that, which informational support is required to help guide us to the right tracks along the many possible ones.

As the ultimate question is about society, the objective of decision support is not just a specific technology or product, but the effect of the choice for one or another option on society, in terms of sustainability. Linking specific actions to these broader consequences is possible in simple or more complex ways. These have in common that they always cover technological consequences in production and consumption chains, from cradle to grave, that is from a life cycle perspective. This guiding metaphor of the ***life cycle*** is the first and central element in the scope of CALCAS. It indicates the close interconnections between production, which starts by taking inputs from the environment in primary production of abiotic and biotic materials and food, goes to final consumption and ends with recycling and final delivery of materials to the environment. How exactly life cycles may be specified is a central subject of the CALCAS project, at the supply side of information for decision support.

So a central scope element is the linking of demand for and supply of sustainability information. The background for posing and answering sustainability questions always is the same: how may decisions at the micro level work out at the macro level, i.e. for total society? This link between micro and macro levels is the ***principle of coherence***. Answers always have the same background, be they operational decisions on products and on technologies or on more aggregate levels of production and consumption, or be they strategic and indirectly relevant decisions shaping the operational ones at a later stage. This does not mean that there is one method and model for all questions and decision situations, nor that everybody uses the same evaluation framework and normative trade-offs.

However, before indicating the answers in terms of the sustainability information to be supplied, first the questions are to be framed more precisely, as a demand for information in specific decision circumstances. This demand specification forms the first element of scope. Next, meeting the demand, as demand driven supply, forms the second main line for specifying the scope. We should be aware that there is always more than one answer possible for any complex question. As a third element in linking demand and supply, a number of options for linking supply and demand will be surveyed and main lines to follow will be drawn.

The demand side firstly refers to what we need to know for well balanced decision making; what are the aspects to cover under the three pillars of sustainability (2.2.1). Secondly, in what contexts are we operating; for what sort of governance and decision situations is the information required? The informational requirements are directly related to the way decision making is embedded in society, that is, for example, to the prevalent governance practices in firms, in governments and in the EU (2.2.2). This general decision making structure is further detailed in terms of the types of questions to be answered, both as to the level of generality and as to nature of the questions involved (2.2.3). These types of questions are mirrored, but not in a direct way, by the persons and bodies who need the information: who are the decision makers to take into account (2.2.4)? Next demand may differ in several respects together, as related to the level of development of countries and regions involved. In developing countries the social aspects may be of prime importance internally, while their role in global industrial (including agricultural) systems may be analysed from very different perspectives than for developed countries (2.2.5). The demand analysis finishes with an analysis of drivers and barriers, to allow for a more dynamic view on the scope of demand, and to indicate how demand partially is a function of supply as well: What is relevant and can be known should be known (2.2.6).

The supply side starts with an outline of terminology, as in several studies differing and overlapping terminologies are used. The general term is Life Cycle Approaches, covering three levels: Life Cycle Concepts; Life Cycle Methods & Models (including ISO-LCA and (new) LCA); and Life Cycle Tools, as software and databases; see also Section 2.3.1. For each the scope covered will be indicated. The chapter ends with a view on how demand and supply may be linked, as a main element for the overall scope of the project.

The scope of the project thus being established determines what is to be investigated and what not, where priorities lie, and how the subjects are approached. The questions raised will be guiding in determining the scope of the CALCAS project, for each of the fields that will be discussed in further detail below.

Conclusions on scope regarding general principles, 2.1

Some general principles on scope have been formulated in this introduction. First principle is the focus on life cycle approaches only, with other types of methods only taken into account if relevant for life cycle based analysis. The life cycle stands for an integrated view on economic activities covering all aspects of production and consumption. This principle guides the selection of approaches to take into account in the SWOT analysis, in **WP3,** leaving out most of the approaches as analysed in A-Test.

The next principle is that demand guides supply, not the other way around. Of course, demand is also formulated in terms of questions on which answers may be supplied, at least to some extent. This principle guides the formulation of the user demand in **WP6**: the question of the user is central, not the tools as existing (e.g. LCA). Preliminary results from WP6 would therefore be most welcome at an earliest possible stage.

A third principle is that all formulations of demand and supply have a unity in background: How can society move towards sustainability? This principle guides the formulation of new LCA strategy and research, in **WP7,** and has a bearing on **all other WPs**.

CALCAS strives at covering a broad set of sustainability views in Europe, and the world, reflected in **all WPs**.

2.2 The scope of demand

2.2.1 Demand for information: environmental, economic & social

Sustainability information concerns the goals to be realised in society. The broadly accepted Brundtland principle of 'meeting the needs of the present generation without compromising the ability of future generations to meet their own needs' has been worked out in domains of needs, with positive elements to strive for and negative elements to avoid. These customarily are grouped into three domains of sustainability, an economic, an environmental and a social one. Prime focus in CALCAS will be on better incorporating environmental aspects, with the analysis broadened by consistently linking economic and social aspects in the same analytic framework.

The goals are not realisable in a direct way as by producing biodiversity or producing climate stability. Such objectives are realised indirectly, through measures influencing the objectives through all sorts of interrelated mechanisms. Therefore the demand for sustainability information in decision support is a demand for indirect information, to make the linking of actions to the objectives and goals. In modelling terms: There are goal variables in terms of sustainability, there are instrument variables, as possible actions to be taken, and there are intermediate variables and mechanisms linking the instrument variables to the goals. The question here is what we should consider as goal variables. These then can be linked to demand by decision makers, through the supply of models appropriate for their decision situations. To take an example from the economic domain, if one aspires a certain amount of economic growth, in terms of GDP or labour productivity, the instrument variables may be defined in terms of research and development activities and investment incentives, which through some model specifying empirical relations, link to economic growth. In this case, the model would have to be dynamic, to catch the goal variable of economic growth. Models may be quantified and operationally filled with decision options, empirical relations and results, but may also be at the level of methods[1], to be filled in more specifically for specific decisions. Without a defined modelling structure, the analysis is qualitative, in terms of concepts.

The analysis of the goal variables of sustainability primarily is focused on their consistent formulation in the causal chains involved, not on their development in content, which requires a more philosophical endeavour. Several relevant aspects may not be analysed adequately in a life cycle approach. Clarification of such boundaries is part of the analysis. Environmental aspects will receive main attention.

Environmental aspects

The scope of environmental aspects covered will be broad in terms of subjects covered and places in causal effect chains in the environment. The demand for environmental information in the past has led to the supply of a large number of environmental indicators. For this reason supply and demand are mixed and often difficult to separate.

[1] Observe that we use the term "method", not "methodology" as some writers do. Methodology is reserved here for the rationale for using a certain method. Wikipedia writes on methodology: "Most sciences have their own specific methods, which are supported by methodologies (i.e., rationale that support the method's validity)".

There are two main lines in available indicators developed in LCA: midpoint and endpoint indicators. The midpoint aspects are the richest in development now, linking economic activities to environmental mechanisms and ultimately to safeguard areas. They encompass the environmental effects as covered in the UNEP-SETAC Life Cycle Initiative (see http://lcinitiative.unep.fr/) and in due time those endorsed in the European Platform on Life Cycle Assessment, but are not necessarily limited to those, neither in content nor structure.

Impact categories covered in UNEP-SETAC Life Cycle Initiative
Depletion of abiotic resources
Metallic minerals
Other minerals
Energy
Freshwater
Land use impacts
Climate change
Species and organism dispersal
Stratospheric ozone depletion
Human toxicity
Ecotoxicity
Photo-oxidant formation
Acidification
Eutrophication
Noise
Casualties
Depletion of biotic resources

Source: Jolliet et al (2004)

They range from a global systems level as with global warming and ozone layer depletion, through regional levels as with acidification, to local level, as may be the case with pollution of soils.

Further effects may be considered. The boundary of inclusion is with:
- site specific environmental aspects
- ionising radiation
- soil erosion
- soil fertility and other soil related impact categories
- salination
- dehydration and water availability
- workers health and safety aspects
- consumer health and safety aspects.

These aspects need to be placed in the causal chains involved, linking economic activities to ultimately relevant sustainability aspects. For example, ongoing climate changing emissions; increased land use for bio-energy; and erosion due to the lowering of water tables contribute to reduced biodiversity each, while their effects may be mutually reinforcing.

The general questions for CALCAS here are the following:

1. What is included in some (ISO-) LCA models and in related life cycle methods and models already, and might be further developed?
2. What is not yet there, but is developing, also in other domains of specialised sustainability analysis?
3. What is available in non-life cycle models but might be incorporated in a life cycle framework?
4. Which research is required to incorporate such mechanisms in life cycle based analysis?

An example of question 2 is the vast knowledge on agricultural pesticides which now is not linked to LCA. The detailed further elaboration of such aspects will not be the subject in CALCAS. However, if the subject is important and the conceptual structure can be made fitting in principle in a life cycle framework, research lines for inclusion of such aspects can be developed in CALCAS.

Though clearly demand from politics is relevant for developing life cycle models, the demand should not be taken literally as stated in public policy documents, nor in private ones as specified for example by GRI (Global Reporting Initiative). These reflect sustainability considerations but not necessarily in a systematic and consistent way. For example, the difference between *lower material input* as a strategy for improving environmental performance of society, and the actual environmental effects of implementing such a strategy often are not made, nor a differentiation as to differences between material resources in this respect. The role of CALCAS is to clarify such issues, analytically in WP3, and linked to demand for sustainability analysis in WP6.

Consistency considerations are essential for overall environmental evaluation, most visibly for the integration of different environmental scores into one overall environmental score. Several methods for aggregation of some or all environmental aspects into one single score will be compared, as based on cost considerations, on values, on public preferences and on private preferences.

Economic aspects

Economic aspects (employment, GDP, etc.) for evaluation are to be strictly distinguished from economic mechanisms (like market mechanisms), and from economic valuation of environmental aspects (like the valuation of health effects of toxic emissions in monetary terms).

The economic aspects as part of sustainability evaluation will firstly cover Life Cycle Costs, both in market terms and as collective costs. The difference between these is formed by taxes and subsidies and market imperfections. Cost measures relate to choices on environmental improvement, as one domain of application. More generally, it is the value created which is the relevant economic factor, as a measure on how needs of current and future generations can be met. In the range from cost to values, several economic variables may play a role, like (cumulative) value added, value created, GDP/GNP, labour productivity, and dynamic variables like economic growth. In CALCAS, the economic aspects relevant for both public and private decision making will be covered preferably in a life cycle perspective, both from a cost and a value perspective.

Social aspects

Social variables will be covered based on ongoing work in the UNEP-SETAC Life Cycle Initiative, replenished with useful input and experiences from the Global Reporting Initiative, the Human Development Index and the Millennium Goals that may be or not be life-cycle based. A number of relevant aspects is at the boundary between economic and environmental goals. Such socio-economic aspects include income distribution and employment levels. The social aspects currently are in development. In UNEP-SETAC, a feasibility study has been published (Griesshammer et al., 2006), which does not yet specify a specific list of social aspects to be covered in (broadened) LCA.

Prime focus will be how these social and socio-economic aspects may be incorporated in a life cycle framework of analysis. Regarding the evaluation of different environmental aspects, and between these and other sustainability aspects, see the subject of evaluation, in Section 2.2.2 on governance below.

Conclusions on scope regarding the nature of sustainability information, 2.2.1
Sustainability is formulated in terms of objectives or goals, covered in three domains. The fundamental discussion on what constitutes sustainability is not part of the project, how important such a discussion may be. However, in terms of ultimate sustainability values, the three pillars of sustainability overlap, all linking to the normative concept of human welfare. Some starting points for normative research are part of CALCAS, both in **WP4**, regarding their integration in governance considerations, in **WP6**, as in systematising the demand for information as emerging from the focus groups involved, and ultimately in **WP7**.

The focus in CALCAS is on life cycle approaches, how these may link choices on technologies to the objectives in the three pillars of sustainability. The prime focus is on the environmental pillar, with due consideration to the economic and – to a lesser extent –the social dimension of sustainability. This acts as a guiding principle for most work in **WP3**, and is the main challenge in **WP7.**

The environmental aspects covered are placed systematically in causal chains linking the system of economic activities (the *inventory* in ISO-LCA terms) to ultimate sustainability values. Possible expansions of the domain of applicable environmental aspects are part of the investigations, again primary related to **WP3 and WP7**.

Economic aspects are covered both from a collective, a governmental and a private perspective.

Social aspects are more in a stage of conceptual development. CALCAS will contribute to that development, by indicating which aspects can be covered now (**WP3**) in different life cycle approaches, and which cannot (**WP7**).

2.2.2 Demand embedded in governance practices

The use of sustainability information is not restricted to public policies and specific regulations. In modern society, there is a diffuse network of mutual expectations and strategic decision

making aligning private decisions and public considerations, at least to some extent. Private actions may be "in advance" to public policies and may even make such policies superfluous. Conversely, public policies may be developed predictably to allow strategic private actions, to avoid costs and create advantages. If mutually aligned, the advance of public policies and private actions may develop smoothly. The ensemble of such public and private actions shaping the development of society may be referred to as *governance* (Rubik & Scheer, 2007).
This observed change in actor constellations has been accompanied by the emergence so called "new" instruments in environmental governance during the past years. These instruments are characterised by a higher level of discretion for the target groups in contrast to traditional command-and-control approaches. Examples of such instruments are economic instruments, framework legislation or a stronger commitment to self-regulatory models. However, this focus on new instruments with a higher level of discretion does not necessarily imply a complete withdrawal of public actors. New modes of governance often take place "in the shadow of hierarchy", leaving coercion as a dominant mechanism intact and thus still allowing public authorities to play a decisive role.

Clearly, without the right means of communication such a quasi-voluntary alignment of actions would be accidental only. Consequently, one new direction in discussions about new governance deals with the role of information generation, transmission, goal-orientation and the potentials of LCA: "Knowledge for transition" – at the example of LCA – aims to steer industry, agriculture, energy production, important actor groups (e.g. associations, NGOs), and other users of environmental resources and ecosystems. One clear role for life cycle approaches is to help set up this communication. Therefore, these approaches, and the sustainability information derived from them, should be adequate for this purpose.
Environmental governance is not an island. Sustainable development does not take place in a separate domain of products and technologies. All societal decisions on consumption and production are embedded in economics, institutions, culture and governance structures. Should these institutional aspects be part of sustainability analysis? Yes, of course.[2] Decision situations are shaped by such institutional factors, including environmental policy instrumentation. To take an extreme, if all environmental effects were endogenised in all prices, also future prices, market forces could reflect the environmental part of sustainability. Life cycle based analysis of technologies and products would be superfluous as a separate means of communication in such a market-coordination-based society. Another extreme is the regulatory prescription of all relevant private actions. Enforcing all regulations would diffuse all relevant knowledge. Acting accordingly would suffice for sustainable development. The data requirements involved and the planning and enforcement problems are enormous, but again, sustainability analysis as a means for communication would not be required. The network approach as sketched above is the only one based on multidirectional communication requiring broad sustainability information. The weakness of this approach is that market coordination not geared to sustainability goals is a powerful means for non-sustainable development. Electricity producers in a traditional, privatised market will not invest in carbon capture and sequestration. This would increase their production cost by roughly 50% and would imply their immediate bankruptcy, unless their competitors would be forced to do so by regulatory means. So the network approach in itself will not function forcefully, if not supported by market adaptation, internalising external effects, or

[2] The EU-financed Epsilon project (http://www.sustainability4europe.org/) even distinguishes the institutional dimension as the fourth pillar of sustainability.

by regulatory means. CALCAS will not endeavour into the highly relevant subject of policy instrumentation as an independent part of analysis. However, life cycle based sustainability information may play an essential role in policy formation, in policy implementation; in creating support for policy development and implementation; and in reducing the cost of policy implementation. These functions should be reflected in the analysis for decision support, focussed around horizontal governance.
One may even go one step further and state that the sustainability subject should have an influence on how governance structures develop. Even if agreed, this would be one step too far for this coordination action.

The governance discussion is about integrating and aligning the activities of different actors with different goals. Summarising, extremes in governance practices can be typified in three ways, here all assuming sustainability goals being covered. The terminologies may be confusing, see for an early survey Thompson (1991).[3]

- *Market coordination*
  For sustainable results, markets would reflect social and environmental aspects, on top of the current mainly private economic ones. This coordination sometimes is named horizontal coordination, to be clearly distinguished from horizontal governance, see below.
- *Vertical coordination or hierarchical coordination* covering all *top-down* policies and including regulations.
  For sustainable results, decision makers at the top are guided by sustainability considerations, and order actors under their jurisdiction to act accordingly.
- *Network coordination, horizontal governance or new governance*.
  More or less equal powered decision makers get aligned in a process of communicative interactions, with each participant reflecting sustainability considerations to a greater or lesser degree. An essential feature is that power and decision competences are based in non-governmental actors, including private persons as both citizens and consumers.

Currently, market coordination is not focused at sustainability but primarily at economic considerations. Exceptions are for example the tradable emission permits as possibly becoming effective for CO2 emissions in Europe and emission taxes in Norway. Vertical coordination is reflected in the IPPC procedures in the EU. It cannot convey the essentials of sustainability for all decision situations; there always is substantial decentralised independence, especially in a technologically dynamic context. And actors in horizontal governance will act from their broader roles and interests, which for most actors will cover collective environmental aspects only to a quite limited degree.

In practice, the three types of coordination are mixed. The motor for sustainable development will be in government departments and NGOs, both having only a substantial but limited power to influence the actions of others. Moving actors towards sustainability therefore also is a soft process, based on influencing and reshaping markets, based on regulatory power and creation of

[3] These ideal types might be linked to political views like enlightened liberalism; a planning type of socialism; and participative democracy or structured anarchism.

power based incentives, and based on discussions to influence actors in the right direction voluntarily, by knowledge and by value based normative incentives.

As a basis for effectively guiding actions towards sustainability, first a common language for sustainability discussion is required, not only covering environmental aspects, but also other aspects involved in choices, especially economic and social ones. With partly horizontal, vertical and market coordination, these cover a broad range of discussions: Within specialised environmental agencies on instrument development, policy development and policy implementation; in decision making groups in firms, from a strategic and R&D level, to detailed design of products and technologies and their management; to information for consumers on their consumption choices and behaviour; and, most broadly, in feeding the public discussion on sustainable development. The common core of detailed analysis will be accessible for specialists only. For effectively supporting sustainability decision making in broader sectors in society, this specialist core is not suitable. Translation of results into more easily understandable terms is essential, as are domain specific extensions and domain specific simplifications. Their development is part of the discussion process, with a special responsibility for the scientists involved, as now in CALCAS. Especially the work in WP6 should give impetus to this work.

Evaluation[4] and priority setting
In all choices regarding set-up of sustainability analysis and the ordering of information for specific decision domains, the underlying criteria of relevance are based on importance, from a normative or value based point of view; they involve evaluation. There is a general agreement on sustainability values, as stated in the sustainability concept and aims, but this agreement is partly based on the generality of the statements at the level of principles. In actual decision making, the principles do not guide directly as there are several, requiring a trade-off between them, as a practical evaluation. In actual decisions, the trade-off is made, implicitly or explicitly, both between different environmental aspects, between economic aspects between social aspects and between social, economic and environmental aspects. There are several strategies to approach the evaluation problem. One may deny it, focussing on one item only, like economic growth, or climate change. In practice one still has to make choices, as between different options for reducing CO_2 emissions. Bio-energy may lead to rapid habitat losses in the tropics, while wind power does not, but hurts birds and requires back-up facilities. Choosing for wind power for this reason is making a trade-off. We assume that different aspects are relevant in practically all choices, and only seldom will there be a dominant alternative, better in all relevant aspects.

There are three basic approaches to the evaluation problem:

1. Case-by-case evaluation. Leave it to the actual decision makers in actual choice situations, and support them with sophisticated multi-criteria analysis (MCA) methods. It then is decision makers who make the trade off on a case-by-case basis, see e.g. Hobbs & Meier (2000).
2. Formalised weighting. Make a formalised weighting scheme stating the relative importance of different sustainability aspects. There will of course be many weighting schemes, but being explicit these may be open to discussion. Monetary valuation is one of the options for formalised weighting.

[4] Evaluation is the overall term, weighting is a formalized form of evaluation and valuation is one of the sub-options of weighting, meaning weighting in monetary units.

3. Cost-effective improvements. Choose options which are as cheap as possible in creating environmental improvements.

See Ekvall et al. (2005), Huppes & Ishikawa (2005) and Eshet et al. (2006) for a survey; Martinez-Alier (1998) supporting position 1; Barbier et al. (1990) and Rabl et al. (2004) for variants of option 2, with Rabl et al. (2004) representing the European Commission; and Oka et al. (2005) giving an example of position 3.

The main distinction between options in approach 2 is between subjective individual methods, the economist approach, who ask a representative panel for their preferences, and collective methods, stating what governments or stakeholder groups including governments define as relevant trade-offs. An example of Dutch government plus stakeholders setting weights is in Huppes et al. (2007). One may also derive implicit weights from choices being made in society, deriving a best fitting weighting set, or from policy goals, which can be connected to costs for realising. Most environmental agencies have some rules of thumb hidden in a drawer.

From a general welfare point of view, disparate choices are a social waste. If in several occasions of climate policy different costs per unit of improvement are involved, shifting to the options with the best eco-efficiency realises the same climate improvement at lower cost. Other shifts may increase climate effectiveness of policy at lower cost, and with the same costs, higher environmental improvements can be realised. One need not be a neo-liberal economist to care about costs. This is the weakness of option one, unless based on broad societal discussions on relative importance. If no convincing or overlapping methods in approach 2 can be agreed upon, approach 3 is a fall back option. The option of cost-effectiveness is implied all variants in approach 2. Most current MCA methods and some weighting methods do not use an adequate normalisation procedure, making outcomes not comparable between choices.

What should be avoided is Lomborg's Copenhagen Consensus approach in setting priorities (see http://www.copenhagenconsensus.com for their 2006 report), which is based on some sort of lexicographical ordering as evaluation procedure. The highest priority subject gets funded; below the line nothing is funded. This danger is inherent in choosing for "persistent environmental problems" as a priority focus. It is not the persistence but the relative seriousness of the problem; the cost for improvement; and the social aspects involved which have to be combined in some weighting procedure in actual choices. See the subject of strategies below.

How do we treat this subject in CALCAS[5]? As actual decision making is to be supported this is an essential element. However, there is no hope that there will be broad agreement in society on any of the options within the three approaches. Even if a method is chosen, the outcomes may vary substantially between researchers. As a first step, clarification of the elements involved in the three domains of sustainability would be of great help. These would have to be defined as mutually independent units, to allow for sensible MCA or other weighting procedures, and be linked to models for their precise definition and quantification. This is part if D17, D20 and D22, reckoning with outcomes of D13.

Giving a well defined modelling set-up - even if only in principle and requiring further research - the most practical solution would be to see if some group with authority could agree on a range of weights as representing broad segments of society, also internationally, with an explanation of

[5] Outside CALCAS: become a member of the Working Group on Modelling and Evaluation for Sustainability, see http://www.wg-mes.com , which now is starting up.

main differences in positions. This could form the basis for a continuous discussion on this essential subject. This proposal could be framed as research of a social science nature, in D22.

Strategic choices and meta-strategies

In actual decision making, there ultimately is a practical level involved influencing activities and through these linking to economic, social and environmental effects. However, decisions are structured in layers (see Section 2.2.3), often involving different groups of decision makers in a slightly hierarchical and often not very connected way (see 2.2.4). Such layered structures form the backbone of how governance is set up, as mixes of market coordination, hierarchical coordination and network coordination, focussing more on direct actions, or cultural and scientific developments, or also on institutional parameters. A main strategic choice, for example, may be to align all policies to the *polluter pays principle*, in one of its more demanding variants. Or one may choose to expand sustainability oriented research and R&D budgets based on the potential contribution of outcomes of research projects to sustainability. Such strategic choices may be the essential ones in the long run, as such choices may influence large numbers of decisions dynamically. There should of course be a relation between the meta-strategies and the action oriented choice trains involving economic activities more directly.

Life cycle approaches can play a dominant role in this regard. On the one hand LCA may be used to place political decision making on a broader knowledge basis. On the other it can serve as a starting point for the production of knowledge, which in turn is committed to the uncertainties and disappointments of open research processes. Within knowledge based approaches of governance in general, the generation, transmission and distribution of knowledge for reducing environmental pressures aims for decentralized, nevertheless collective decisions. However, while the value of knowledge based approaches for new forms of governance is generally accepted, there exists no general rule to explain at what point in the policy cycle these tools should be used, i.e. whether during the process of policy formulation, implementation or evaluation. In addition LCA possesses the "risks" of uncertainty, of methodological pluralism and of missing acceptance due to "open" scientific processes. Especially WP4 will therefore deal with questions like

- How and to what extent can LCA contribute to new forms of governance, to a better and leaner regulation?
- Which experiences exist with regard to LCA as an information generating tool in policy *formulation*? Could LCA provide public decision makers with better information during policy *implementation*? Is LCA used as a tool for policy *revision*?
- Which experiences exist about direct or indirect incentives by policy about the application of LCA within business and society?

The levels of choice will be discussed below. For the governance discussion, it would be essential to define the fora of stakeholders relevant for the strategic levels of discussion and choice, in WP6. It is clear that working out such lines of thought requires a substantial amount of work, involving others than the current participants. Defining this work as an integrated research task is within the scope of CALCAS, however.

Conclusions on scope in relation to governance practices, 2.2.2
Main modes of coordination have different requirements on life cycle analysis. Horizontal governance at the level of sustainability strategy formation requires overall insight in how society can develop towards sustainability, including questions on how priorities may be set. At the other extreme, consumer choices on products require simple comparative information. In principle, the scope of CALCAS covers all types of governance, at all levels of decision making, and for all questions arising there. The focus is more on clarifying these complex relations than on filling in one part as a detail.

The horizontal, network approach to coordination may easily lead to diverging and disconnected methods of analysis and evaluation, leaving society in a non-directed high cost low environmental quality state. Reckoning with actual differences, a central scope question is how underlying unity of analysis can be safeguarded while meeting the different types of demand.

Evaluation, though essentially subjective and value based, is a central element in practical decision support, both at a strategic and at an operational level. Clarifying the main structure of what can be evaluated is part of CALCAS (mainly **WP3** and **WP4**), while indicating how diverging positions can be related and reconciled to some common ground will be part of research programmes to be formulated in **WP7**.

Similarly, the relation between on the one hand technology oriented choices, including search strategies like ‘recycling more’, and on the other hand the meta-strategies which only indirectly influence development of technologies, is an essential part of governance discussions on sustainability. Clarifying the field to allow for focussed research is part of the scope of CALCAS, being worked out in **WP4** and leading to research lines in **WP7**.

Knowledge on the background of governance structures is essential for focus, but the active development of governance structures is not part of CALCAS.

The detailing of these governance considerations takes place in **WP4** and is reflected in how user needs are approached in **WP6**, how research programmes are set up in **WP7** and how results are disseminated in **WP8**.

2.2.3 Demand in terms of questions to be answered

The central focus in CALCAS is on questions regarding choices on technologies and products: How can these choices contribute to sustainable development? However, such questions can be framed from diverse angles, depending on the choice situation and the role which different actors involved in the choice may play. One may doubt the relevance of the thousands and thousands of micro level decisions assumed to contribute to sustainability, if these cannot be placed in an overall structure of a more encompassing nature. Such considerations are legitimate and in developing life cycle approaches should receive prime attention. If it were possible to avoid having to support the myriad of micro decisions, by using a more encompassing approach at meso or macro level, this indeed would be most desirable. Are there concepts which indeed give guidance enough to guide actions, like *dematerialisation* and *recycling*? Or are these strategic search principles only, to be corroborated at a more detailed level of technologies specification? So a first line of analysis in terms of questions is on their level; on how encompassing they may be formulated, in an answerable way. Even if the outcome may be that the micro level questions are essential in the end, the meso and macro level questions may bring focus to the relevance of the micro level, and may help shape micro level questions.

As to the specific questions one may want to have answered, these can vary along a large number of dimensions, each with requirements for the most apt form of life cycle analysis. For example, in developing new product-technology combinations the questions posed require essentially different methods for analysis than for product improvement or purchasing decisions. By enumerating a number of dimensions, we now can indicate the variety, and hope to develop a supply structure which can cope with the variety in a most efficient way.

So this section indicates the scope of CALCAS in terms of levels of questions, in 2.2.3.1 and as to main dimensions on questions to be taken into account, in 2.2.3.2.

2.2.3.1 Levels of questions

Questions can be framed as to their level of aggregation, at a micro, meso and macro level. There may be quite some discussion about exact boundaries between these levels, but agreement on the existence of different levels, more as a continuum. Especially the higher level questions may be difficult to answer, and surely not in this coordination action. The task of CALCAS is to define how some of these questions might be posed in a way that they become answerable, through research.

- Micro: Specific product questions. How do alternative options for products and required technologies in the life cycle compare in terms of sustainability performance, how can we improve performance in a balanced way?
- Micro: specific technology questions. How do specific technologies, with their products involved compare in terms of sustainability performance?
- Meso: Strategic product questions. How do different consumption profiles compare in terms of sustainability performance?
- Meso: Strategic technology questions. How do alternative options for technologies in a domain compare in terms of sustainability performance? For example, how does Nearly Zero Emission Coal technologies compare to biomass based energy systems?
- Macro: Strategic choice questions: what approaches to improved sustainability performance can we choose? For example: can we relate closing loops; dematerialisation; decreased energy use; moving to a service society in a convincing way to improvement in environmental performance?
- Macro: Strategic background questions. How is society, or a specific country, or a technology domain, developing in terms of sustainability? At this level, the IPAT equation (Impact= Population X Affluence X Technology, see Chapter 3) holds, with several differentiations possible in all four covering variables.
- Macro: Insight in structure. How are relations between activities structured and how may they be restructured. For example: Mass flow relations and monetary relations between processes and sectors give insight at a higher level than specific technology relations.

The scope of CALCAS has the micro level of product questions as a starting point but extends to the higher macro levels, as far as such higher levels are required for sustainability decision support, which seems obvious

The level of question does not directly correspond to the level of supply. Ideally, all micro level questions are answered in terms of macro level effects of the choices involved. For example, when comparing hybrid drive buses to fuel cell buses, a micro level choice, the overall effect on society is to be reckoned with, possibly involving modelling at a meso and micro level, in addition to the micro level technology specification and analysis.

2.2.3.2 Types of questions

Developments in LCA questions lead to ever broader scope of the subjects decisions relate to and hence to broader questions to be answered. ISO-LCA has focused on micro product questions primarily. More encompassing questions and requirements on answers follow a distinct pattern. Questions have moved:

- from retrospective to a prospective assessment
- from assessment of single products to product families
- from justification of what has been designed or produced to innovation support
- from single product–technology combinations to multi-product-technology combinations, shifting focus to technologies.
- from simple product questions to questions on larger scale consumption domain and on broader technology groupings.
- from ‘arbitrary sized’ functional unit comparisons to totals considered.
- from product-specific effects on the environment to insight in the place of the products considered in an overall sustainability performance of society.
- from the environmental domain to also covering the economic and social domain.

These shifts are reflected in the scope of CALCAS, leading to new requirements on supply. Answers shift from taking into account technological relations only, to covering broader mechanisms. These mechanisms may cover systems specification, as in shifting shares of technologies at increased demand for a product, to economic consequences of technologies beyond the functional unit analysed, as in land use consequences of large scale biomass production, and to consumer reactions on shifts in price-product combinations. Broadened questions lead to deepened and broadened answers, with these in their turn leading to new rounds of questions for LCA. The subject of rebound, for example, is not just a matter of ‘better supply’, but also of new types of questions coming up. The rebound subject has negative connotations. For example as the effect of more efficient cars in all sizes, which actually happened, has been much reduced by an overall shift to larger and heavier cars. Similarly, the introduction of high-efficient light bulbs has been combined with an expansion of the number of light points. Rebound seems to stand for behavioural mechanisms not normally covered in ISO-LCA, involving economic, social and cultural mechanisms. It seems wise not to define ‘rebound’ precisely, but see it as a subject of broader mechanisms to take into account in decision making.

The following list of dimensions on question types is given in an enumerative way. More dimensions, also relevant, may be added.

1. Past, present, future. A main distinction is between questions on past and current performance and business-as-usual extrapolations as background information, versus questions on improving future performance, i.e. choice questions, based on analysis of alternative options.
2. Before-after comparisons, diachronically ("through/across time") as improvements, and comparisons between alternative options in the same time frame, synchronically[6], as a basis for decision making.
3. Satisficing (Cyert & March, 1963) and optimising. Framing of choice questions as a basis for "enough improvement" or optimising/maximising.
4. Optimising or choosing. An LCA study may be performed for optimising a specific process or product, or it may be performed for choosing between alternative (process/product) options.
5. Operational choice versus strategic choice. Alternative options may be specified in detail or in more general terms, with possibly later more detailed choices. The problem then is how to link strategies, not yet filled in operationally, to their expected sustainability performance, requiring analysis at a meta-level.
6. Generality of question. The range is from occasional choices in uniquely defined circumstances versus more broadly framed questions. For example: 'Is it better from a sustainability point of view to take the plain or the car today, knowing that the flight will take place anyway and will fly half empty and I will drive with three persons in my car today', or 'Is it better from a sustainability point of view to go by air or by car, under some general assumptions about average conditions.')
7. Time horizon of question. The range is from short term reckoning with current technologies, to long term reckoning with future technologies.
8. Integration of sustainability concepts. The range is from a detailed survey of all relevant aspects as empirically modelled; to integrative measures like eco-efficiency; or, as in a monetary valuation approach, to a single monetary "overall sustainability" score.

[6] These concepts are used both in a historical studies, in cultural studies and in decision theory.

Conclusions on scope in terms of questions, 2.2.3

One first main expansion in scope as compared to ISO-LCA is to move from product analysis to also covering Life Cycle Technology Analysis (LCTA), being linked to several products. An example is the enzymatic conversion of lignocellulosis into sugars and ethanol, essential for increasing the use of biofuels substantially. The link to current TA assessment approaches is to be made at a conceptual level at least, as the TA groups may be diverging from the sustainability analysis groups.

Innovation in LCA is focused in a framework linking micro and meso questions on products and technologies to macro level sustainability questions, and to higher order meta-strategy level questions related to governance for sustainability.

Prime focus is on future oriented questions as opposed to questions on past performance, and on synchronical comparison between future states as opposed to diachronical analysis of before-and-after states. Quasi-dynamic and dynamic analysis may follow.

Outside the scope are single choices without a general bearing.

The formulation of questions relates in a general way to what is required in different governance and decision situations, in **WP4**, and in the adequate formulation of user needs, in **WP6**.

2.2.4 Demand from different decision makers

Decision making in society is structured by the modes of governance present. This general subject has been treated in 2.2.2 on governance. There is a more practical level at which the discussion may return, linking to main groups of decision makers, which have not yet been discerned there. A basic distinction is between decision makers creating sustainability considerations and those following sustainability considerations due to drivers as established through social, economic and regulatory mechanisms. The prime movers in sustainability questions rising are in the domain of public policy development and that of the public discussion regarding sustainable development. There is no clear delineation of societal groups involved, like environmental NGOs covering the demand on environmental analysis. Firms and business organisations like the World Business Council on Sustainable Development (WBCSD) clearly play an independent role in the discussion. The point made here is that the contribution to discussion if coming for example from business is not based on specific business interests but on an independent contribution to the specification of sustainability goals. Only as a second step are these brought in relation to business activities and business interests. We thus may distinguish between prime sustainability decision makers in government and public discussion, and their questions, and derived decision makers trying to accommodate their decisions to the results of regulatory and public opinion specifications of sustainability, and posing their derived questions. In analogy, we can make a distinction between the basic sustainability questions and analysis, and the translation to questions at all other levels in society, involving an element of communication and persuasion.

The prime focus in CALCAS therefore can be envisioned along two lines: how to set up the most adequate analysis in principle, and how to make the analysis available for practical decision making in society. The first level is related to combining policy principles and values and scientific knowledge into more specific modes of analysis. The second level is on how to translate these abstract modes of analysis into practical decision support, covering the range from principles of life cycle thinking and approaches, to applied methods and tools. This one way presentation of development reflects logical structure more than social practice, which will always involve double-loop learning by communication and exchange of knowledge.

For the first more theoretical part, there is a prime role for decision makers at the strategic level of sustainability, in close connection to the scientist involved. This cooperation can be seen in specific domains like the IPCC discussing climate change. A similar role is there for the International Panel on Natural Resources currently being set up at UNEP, with a clear role first for deepened and broadened life cycle analysis.

For the second practical part - simplifying the methodology or simplifying the information coming out of more complex models - should serve major decision makers in relation to their technology and product related choices. Their frameworks and practical wishes should be taken into account, as their influence on future sustainability is essential. These involve persons and organisations in technology and product development at all levels, both in public funding institutions, in private financing organisations and in staff organisations in business strategy development and implementation. Regulatory bodies for policy implantation are in a similar position. They need to know how they can contribute to sustainability through regulatory mechanisms. The role of CALCAS is not to help develop business organisation and public regulatory mechanisms. The role is to provide information to help guide these decision makers, also as stakeholder groups, on the right tracks for sustainable development by giving the relevant sustainability information. The role of consumers is a much derived one only. Their choices contribute to sustainability, as in buying green products, and by doing so they create an incentive for firms to reckon with these sustainability wishes of consumers, by developing the right technologies and products.

Some main groups of decision makers involved in sustainability decision making are the following

- Governments in terms of policy making and implementation
- Citizens, NGOs and other stakeholder groups involved in public policy development and implementation
- Firms, as developers and optimisers products and technologies
- Research and development organisations involved in product and technology development
- Public financing bodies giving directions to research and development activities
- Private financing bodies giving directions to investment decisions on products and technologies
- Firms as producers of existing technologies and products
- Firms, consumers and governments as purchasers of existing technologies and products.
- Retailers and funding organisations as key organisations for creating new products and markets.

- Business associations, as coordination groups for discussion on sustainability options and policies.

Conclusions on scope related to decision makers, 2.2.4
Also within a to some extent network-coordinated society, two levels or foci of analysis may be discerned. One is linked to the developers of new integrated views on sustainable development linked to advanced insight and relative complex modelling, and involves scientists, NGOs and public organisations. They are involved in public discussion and public policy making on sustainability, specifying the ultimate demand for analysis, in a basic sense asking for and supplying “the right analysis”. The other group is more involved in applications, from strategic to practical decisions regarding technologies and products, covering representatives from a regulatory, financing, business, and consumer background. Their questions diverge related to specific situations, as speciation of the general sustainability demand formulation, requiring more detailed analysis, while on the other hand in many situations requiring a simplified analysis to allow for practical or even routine sustainability decision making. CALCAS is to cover both levels, and is to relate them explicitly.

This subject is of central importance in relation to governance in **WP4** and to user needs in **WP6**, as the approach indicated would lead to a distinction between primary sustainability demand, from a general perspective, and derived demand in specific applications.

2.2.5 Demand from different geographic regions

There is a difference in needs for decision support in different global regions, directly related to the choices to be considered and the priorities being set. The style of governance, the environmental policy framework, the level of economic development all set directions on demand. Japan has managed a long period of limited economic growth in the last decade with an integrative view on sustainable development developing, while China has to set priorities on economic growth, reckoning with environmental and social aspects only for those with highest priority now. A detailed product oriented analysis is hardly relevant for Chinese and Indian development now, apart from being conducive to export performance. Also, regions differ substantially as to the environmental problems to be tackled, as in terms of drought and primary resources depletion. Life cycle analysis in developing countries therefore will have more emphasis on strategies, with sectoral analysis as on building and energy sector, and macro level analysis as in material flow analysis.

The analysis will be focused on Europe with some specific analyses extended to other advanced countries/regions (mostly North America, Japan) on the supply side and on developing countries’ specific needs on the demand side.

Conclusions on scope as related to geographic region, 2.2.5
The scope will focus on life cycle analysis requirements for Europe and similarly industrialised countries, while actively investigating how demand from developing countries differs and might be incorporated in the life cycle approaches investigated.

This subject is to find a place in **WP6**, more explicitly then now is the case; will lead to new research questions in **WP7;** and will guide dissemination beyond the EU, in **WP8**.

2.2.6 Demand: its drivers and barriers

Drivers

Sustainability goals may be given for society at large, but they neither fall from the air in a void, nor do they function “in general”. In effect, it is specific parts of public organisations and specific parts of civil society which are actively motivated to help direct actions of others towards sustainability, being drivers themselves and creating driving forces in society.

All sorts of mechanisms may help others to align their actions towards sustainability, or prevent them from doing so. If all regulatory activities were based on the same type of sustainability reasoning, modelling and evaluation, then all private actors would have an incentive to place their decision making in that framework. Then, for example, corporate sustainability may profitably be implemented at all levels of decision making in the firm, driven by well founded expectations on future regulation, by built-in drivers in public policy, by easier access to investment capital for green investments, by support in marketing, by satisfaction of personnel for being able to work in such a public spirited company, and by support for the societal *licence to operate*. Coming to a complete agreement with all parties may not be possible fully. Trying to get there is surely helping to create all such direct and indirect drivers for using sustainability information in mutually reinforcing decision making. Life cycle information, reflecting appropriate goals and being broadly accessible in decision making network, can help set up the information basis for communication. Information is not policy; however, it is a prerequisite for good policy development and decision making.

Clearly, the driver subject is essential in moving society in the right directions. It should be possible for actors involved to know the right way to go; they should be able to generate or receive the relevant information. And they should have the right incentives to take the information into account in their decisions. But how far should we go in CALCAS in specifying such driver mechanisms, and the differentiations of specific information needs in specific decision situations? Firstly, it seems that generalisations on such drivers for information and action are difficult to make. There are several interesting subjects, like how to integrate sustainability information in policy instruments and implementation, or on organisational aspects for environmental strategy development in the firm, or on creating a better framework for sustainability decision making by consumers. Such questions are mainly beyond the scope of this project, and probably would require a differently composed team. We go out as far as possible already, in dealing with a broad scope of question types and a broad set of decisions and decision makers involved, combined in a mixed at least partly new/horizontal governance context. One specific element will be covered however: how life cycle information can be covered in policy instruments. This subject will be treated exemplary, with research ideas formulated only if a main line comes up.

Barriers
Barriers may firstly be defined as lack of drivers and incentives. Development of these has been placed outside the scope of the CALCAS project in the previous section. Also drivers and incentives pointing in different directions than sustainability, like created by globalisation of markets, may form substantial barriers, but clearly beyond the scope of this project.

There may also be barriers in terms of the practical availability of information, either because the receiver cannot handle available information, or because the practical tools for creating the relevant information are lacking.

The subject of how to transform and communicate available information is a demand question related to decision makers and the types of questions they are involved in (see above). Such questions will further be the subject of WP6, user needs. The lack of practical tools is a subject for supply of information, as specified in terms of software tools and data (see below).

Conclusions on scope regarding drivers and barriers for sustainability information, 2.2.6
The subject of creating drivers mainly lies outside the scope of CALCAS, belonging to a broader and different domain of more policy oriented analysis. Some more limited aspects fall under the heading of governance (**WP4**), especially the development of communication tools reflecting relevant sustainability considerations. Barriers to the use of sustainability information partly are of this policy nature as well and then fall outside the scope of CALCAS. Some practical barriers on the supply of information, like lacking availability of tools software and data bases, will be treated under that heading (**WP6**). Summarising: we intend to point at some drivers and barriers but it is beyond our scope to elaborate them.

2.3 The scope of supply

2.3.1 Supply of life cycle approaches: terminology

There is a vast array of approaches to life cycle based analysis (Wrisberg et al., 2002; Ness et al., 2007; Van Berkel et al., 1997; Emilsson & Tyskeng, 2004, Finnveden & Moberg., 2005, Kytzia & Nathani, 2006; Wanyama et al., 2003). Also, there are several ways for ordering the tools, instruments and models, or whatever they are named. There is not one “right” way to do so, but to avoid confusion, some main lines of terminology will be adopted here. One main distinction goes back to the CHAINET project in FP5 (Wrisberg et al., 2002), which distinguishes between concept, as approaches of a general mainly non-quantified nature, and quantified models and tools. We follow this basic distinction. The next distinction is between methods and models with a general nature, like *LCA* and *CBA* and the specific tools in terms of software and data bases supporting such general analysis, like *Gabi* or *ecoinvent*. As there is no software and databases for life cycle concepts, three main categories of life cycle approaches result, see Figure 3 below. This three level distinction is similar to the one developed in the Sustainability A-Test (http://www.sustainabilitya-test.net), see **Table 1** below, equating 'framework' and 'concept' (see also Appendix B). The term concept is chosen here, so the term framework can be used as in 'scientific framework' without causing confusion. The tools level is filled in slightly differently in A-Test, involving several general techniques like *participatory tools*, *scenario tools*, and *multi-criteria analysis tools*, and specific variants of these. CALCAS focuses on the life cycle type of sustainability analysis, of which such general tools may form a part, but does not include them in the analysis independently. Many more classifications are available, but mostly developed for specific purposes. An example is by Wiedmann et al. (2006) in **Table 2** below. The distinction there is between general methods (falling in our category (Methods & Models) and specific (UK) models, which might be classified either as models or as tools.

As most quantified models have been implemented in software, the boundary between Methods & Models and Software & Databases as Tools is not always sharp. For example, there are applied Computable General Equilibrium models with environmental extensions (EnvCGE) like GEM-E3 which may either be classified as models, but which might also be seen as software tools incorporating databases. If commercially available as software tool, the choice is clear. If maintained by a research institute for development and application to specific subjects we tend to classify them under methods and models. Similarly, the boundary between data and software is not clear-cut. Many software packages for LCA are shipped with integrated databases, and a spreadsheet with data and formulas can likewise be considered as a mix between data and software.

Within the Methods & Models category, the generality criterion might be used to distinguish between methods, of a general nature, like LCA and CBA, and models as specific applications of such methods, like 'EU Platform' LCA or United Nations-CBA. As such boundaries are not sharp, such a further distinction would not add to clarification. Similarly, one might indicate a distinction between more product-oriented analysis, substance and material oriented analysis, and economic analysis, as suggested by the examples in the figure. However, such distinctions are not sharp. The product analysis of iron and the material flow analysis of iron may substantially overlap. Terminology is also vague: what some refer to as a life cycle study is referred to by others as a material flow study. Also, there is strong pressure to incorporate economic mechanisms in LCA, while monetary IO models may well be combined with ISO-LCA, either as hybrid LCA or as a more general type of life cycle analysis covering larger sets of products together, as technology analysis or sector analysis. For the purpose of further classification, it seems wise not to further develop categories, but to use the descriptive framework as developed below and the scientific framework as worked out in Chapter 3. In this section we will clarify the scope of CALCAS in relation to the three main categories distinguished till now.

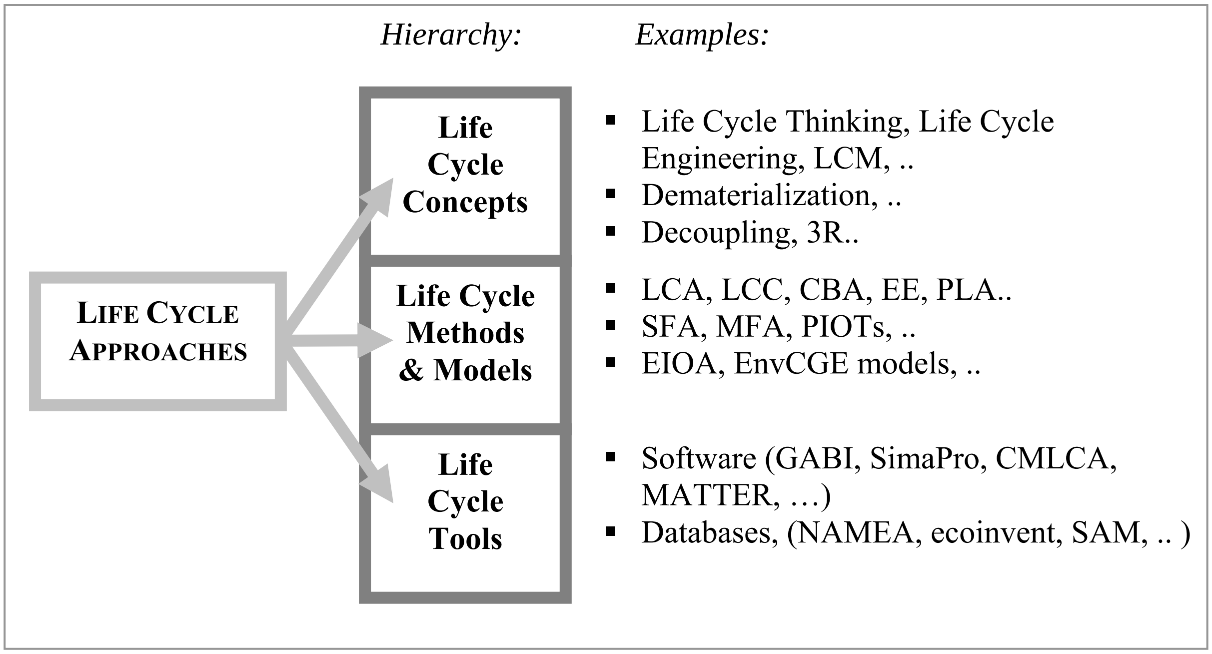


Figure 3: A hierarchy of Life Cycle Approaches for Sustainability Analysis and Evaluation (see Appendix A with list of abbreviations)

As to the applications level in specific decision situations, these have been worked out in Section 2.2, the scope of demand. However, several tools may be linked to specific contexts, both in terms of one tool contributing to another (for example NAMEA, to EnvCGE) or in different decision contexts (for example SFA indicating risks, limitations and options of using specific substances).

A different line of tools involves the social procedures involved in decision making. Examples are participatory tools, like the Stakeholder Dialogues and the social procedures implied in network coordination. A survey from a public policy point of view is in Gramberger (2001). It is a challenge to keep these two types of tools analytically differentiated, not treated on a par as in **Table 1**, but to have them mutually aligned. One interesting integrated combination is the interactive scenario development method, which builds on an analytic framework which is open to non-specialist input formulation, and then links to a procedure to generate relevant scenarios in the discussion or decision domain involved.

Table 1: Main structure of sustainability A-test (slightly adapted, see Annex 2.1 for the original version)

▪ Assessment frameworks
▪ Models
▪ Tools
    • Participatory tools
    • Scenario tools
    • Multi-criteria analysis tools
    • Cost-benefit and cost-effectiveness analysis tools
    • Accounting tools, physical analysis tools and indicator sets

Table 2: Material Flow Methodologies as by Wiedmann et al (2006)

Category	Methods included
General Resource Flow Analysis Methods	Economy-wide Material Flow Analysis Biffaward Bulk Material Flow Analysis Physical Input-Output Analysis/ NAMEA/ Environmental Input-Output Analysis Substance Flow Analysis Lifecycle Inventories (LCA)
Specific Methods with direct sustainability reference	Ecological Footprinting Environmental Space
Specific Hybrid Methodologies	Waste IO Hybrid LCA Environmental Input-Output LCA
UK resource flow models	Stockholm Environment Institute - REAP Cambridge Econometrics - REEIO Best Foot Forward – Stepwise University of Surrey – Regional Material Flow Accounting Model

Conclusions on scope regarding terminology, 2.3.1
The terminology as proposed here does not indicate scope but helps to create precision in defining scope. For example, participatory tools, scenario tools, and multi-criteria analysis tools are excluded for independent analysis, not being life cycle based nor having an inherent focus on environmental aspects. The terminology choices have a bearing on **all WPs**.

2.3.2 Supply: How broad and deep may we go?

Academic curiosity is essential in development and thus the supply of tools, but it should always match with the demand for tools and not drive the development of tools as such. It is the two levels of demand in terms of decision makers distinguished which should guide development, the prime strategic sustainability decision makers and the secondary ones, with their demand modulated as to the questions to be answered in specific governance practices and related question types.

A first element of supply refers to its generality. CALCAS will cover a broad range of Life Cycle Approaches. These (also covering general frameworks) will be surveyed extensively, with as a central question how these may guide decision support related to technologies in a scientifically valid way. At the other side are the tools in terms of software and data bases. That subject will not be part of CALCAS, though questions on practicability are part of CALCAS when considering broadened and deepened life cycle methods and models. As part of WP3, a simple case study will therefore be developed to illustrate the practical application of some of these

methods and models. This case study will be designed with the aim to demonstrate how various methods and models are typically used in various areas of a study, and give insight on different aspects respectively.
The broadening of analysis is quite straightforward as to principles but quite difficult in practice. It requires clarification and further development through research. Clarification especially relates to what and how aspects can be taken into account from a life cycle perspective. For instance, can changes in biodiversity be brought into life cycle tools in a sound way? The deepening options are more complex to evaluate. Two dimensions have been chosen here to depict options, the scale level in terms of aggregation of activities in the analysis and the treatment of time, with dynamic models also incorporating more empirical mechanisms.
By incorporating empirical mechanism a dynamic analysis may be created, not any more linked to a functional unit as specified in ISO-type LCA but linked to totals involved in society. Certain product alternatives which may prove favourable in a static LCA study, may then come out quite differently from a longer term dynamic perspective, for example through cumulative depletion impacts of non-renewable mineral use or expanded use of biomass and the subsequent enlargement of cropping area.

More or different dimensions might be used, like local specificity or encompassing nature on environmental aspects, and other sustainability aspects.) How to assess the interregional specification of product chains, i.e. the circumstance that the life-cycle-wide impacts hit different regions differently? Regions may vary with regard to vulnerability or susceptibility for impacts; and often, decisions are taken in manufacturing countries - based on conventional LCA - which focus on nearby effects with the consequence that impacts tend to be outsourced to other regions, often to developing and transition countries.

The scale level of aggregation is not a matter of either-or. On the contrary, the scope in CALCAS is to focus on linking these levels, as micro and meso level choices are mostly to be placed in a macro level sustainability perspective. The second dimension, the time aspect, is in terms of the set up of modelling, to be clearly distinguished from the timeframe of analysis. Long term sustainability questions may well be answered with scenario-type steady state models.

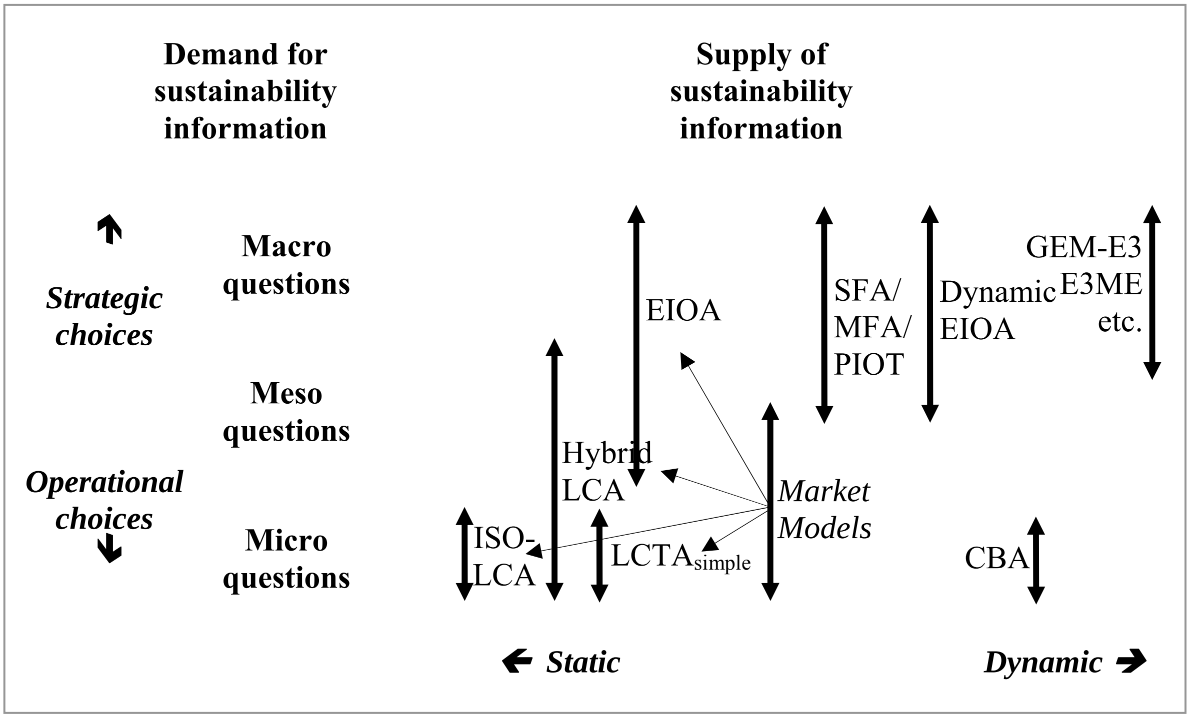


Figure 4: Deepened LCA: what to encounter (with a focus on static versus dynamic models)?[7]

Using these two dimensions, a number of exemplary methods and models can be placed in Figure 4. The focus here is on deepening of life cycle analysis. The starting point is current ISO-LCA as a steady state type of analysis from cradle to grave, in the down-left corner. A first extending step is on the subject of sustainability analysis, on what is being analysed. This subject in LCA is a product function covering the technologies involved in the production, use and discarding of the product. Technologies may be analysed in a more general way, covering all products involved, as simple Life Cycle Technology Analysis ($LCTA_{simple}$; not a standardised abbreviation), and analogue to ISO-LCA as a simple form of LCA. This extension of domain can use the main part of the ISO-LCA method, but avoids main parts of the allocation step, and hence also departs from the single functional unit as a basis for comparison. Next to this domain extension is the option to link ISO-LCA and LCTA to environmentally extended input-output analysis, EIOA. This extension places specific products and technologies in an encompassing scientific framework, allowing for a link of the micro performance to a meso and macro level where many sustainability aspects reside, for example relating some technology development to its contribution of climate change reduction. Though the principles and mathematics of this extension to Hybrid Analysis have been developed, the conceptual interpretation, consequences

[7] In a later stage of the CALCAS project – based on the results of Chapter 4, WP3 and WP5 – methods and models may also be sorted by more concrete information on other aspects covered (than environmental ones) such as economic and social aspects.

for functional unit use, and the precise way of linking need further development. This is to be indicated more precisely in CALCAS. The analysis can remain of the steady state type.

Next to the environmental part of life cycle approaches, the economic and social aspects are to be incorporated in the same scientific framework, thus broadening LCA. A clear distinction should be made between empirical mechanisms of a social or economic nature, as incorporated in deepened models, and the social and economic aspects which are part of sustainability evaluation. Economic aspects already are covered in LCA, as in Life Cycle Costing, while options for adding social aspects are being investigated. It seems that more encompassing models may more easily cover social aspects. The link to EIOA seems quite relevant in this respect, as many social aspects can more easily be framed in an IOA context, like the place in income distribution, the value added per working hour, etc.

The more fundamental deepening steps involve the incorporation of more mechanisms in life cycle analysis than the technology relations now used. This incorporation can be in the form of additional modelling, to specify the inputs in the steady state LCA or in terms of modelling further consequences of the steady state analysis. Market models, for example (themselves being partial and non-life cycle models), may be used in indicating relevant processes to take into account in LCA. Applying them to results by means of soft-linking (see Section 3.5), they may be used for indicating part of rebound processes, as in specifying the consequences of easier home working of fast internet connections to private houses, or in indicating land use consequences of increased land use for biomass-for-energy production. In this use of market mechanisms, or other mechanisms, the steady state model receives input, and its outputs are better interpreted. This way of incorporating more mechanisms leaves the structure of steady state LCA intact. The mechanisms are not endogenised, as part of the model.

Central in endogenising mechanisms is to make the model time specific. At a micro level, the simplest time specified model is that of Cost Benefit Analysis (CBA). It seems well possible in many instances to make a mainly time specified description of cradle to gate systems, as has been done extensively in CBA, Life Cycle Costing and similar approaches. Adding the environmental aspects and possibly social aspects seems well possible with similar difficulties as in adding economic and social aspects to environmental LCA. Making the model time specified does not yet imply that mechanisms have been endogenised; they may be used independent from the CBA model. The CBA model, with impact categories of e.g. ISO-LCA, has a number of advantages as compared to steady state LCA for sustainability analysis. Specifically, by allowing for discounting procedures, the analysis is closer to normal economic analysis of investment options. Also effects on future generations require a time specified analysis. The time specified analysis can be seen as a step before steady state LCA, collapsing the CBA in time. This potential step requires further analysis in terms of requirements on system boundaries and other consistency subjects.

The deepest jump is to incorporate mechanisms endogenously, as in most advanced models for dynamic EIOA and in economic-energy-and-environmental models, like in Europe GEM-E3 and E3ME. These models take into account market mechanisms, income effects, investment functions, etc, and in that sense are more realistic than steady state LCA models. The interpretation of steady state LCA models as to sustainability scores of technologies is much more straightforward however.

Conclusions on scope in terms of broadening and deepening, 2.3.2
Steps towards broadening will be investigated actively and in depth. The scope of CALCAS also involves the investigation of how deep we may go in modelling for technology related sustainability decision support. Though some answers seem probable, like CGE models being one step too far for the moment, such conclusions should be founded on an investigation as what might be made possible by adequate research. The criterion remains: may choices better be supported by making the step to such much more complex models, now or in due time sometimes with a substantial research effort.

The steps towards deepening of LCA will first follow options in depth which remain in the realm of steady state or comparative static equilibrium analysis as central modelling mechanism. Steps towards endogenising more mechanisms in LCA, leaving the integrative platform of steady state analysis, will primarily be investigated at a conceptual level only, to see what might become possible. Relations with non-life cycle based concepts and methods which do not link to the micro level of technologies similarly will remain at the more general level of indicating potentials. The broadening and deepening of supply relates to **WP3** and deeply to **WP5** and **WP7**, guiding the core of developments there.

2.3.3 Supply in terms of concepts

Sustainable development is the most general demand side objective, at the systems level of society at large, taking into account the risk of problem shifting. Practical decisions always have a more limited scope but are part of this overall development. The ***Life Cycle*** concept has developed as one approach to reckon with effects beyond the local scope of the decision, as one step towards the ultimate demand question: how do my options for choice relate to sustainable development. Before answering questions on a quantified basis, always cumbersome, one may try and find higher order strategies which may guide decision making. A most general approach emerging at the concept level is ***life cycle thinking***. It may apply at all levels of aggregation from micro to macro; for all types of decision makers; and for all decision situations. Like sustainable development, it firstly is a strategic concept, which next can be filled in with more detail. ***Life cycle thinking*** expresses the systems idea as a basis for answering sustainability questions. Consumption means production and discarding the product after use. Materials use implies materials inflows and their accumulation and outflows. Sometimes life may be simple: don't make hazardous substances if there is no good reason for doing so, as somewhere in the life cycle you will encounter them. Then life cycle thinking suffices. Some concepts are abstractions from quantified methods, like Factor X, Decoupling and Eco-Efficiency, which indicate that we should strive for a substantial (a semi-quantitative concept) reduction of our environmental impacts per unit of economic welfare; that we should not just go for piecemeal adjustment.[8]

[8] It is interesting to note that a concept like eco-efficiency is used in two different ways: as a qualitative concept ("creating more value with less environmental burden"), and as a quantitative indicator ("economic value per unit of environmental burden").

Some concepts are based on the notion that it always is material things which lead to environmental impacts, so reducing the material inflow will reduce the material outflow. 3R (Reduce, Reuse, Recycle) reflects these ideas, similar to Dematerialisation. The reduction of total primary resource inflow will be right environmentally speaking on average and hence may be a powerful tool for aggregate ex post performance measurement. The relation to technology decisions is less clear. Such concepts may be seen as strategic approaches to direct technology development, which next can be analysed in more detail in the three sustainability domains.

Conclusions on scope in terms of concepts, 2.3.3
All concepts for sustainability analysis that relate production and consumption to environmental and socio-economic impacts will be covered. The central question concerns what their predictive value is in operational sustainability terms, as this qualifies them for use in decision support. These strategic concepts may be derived from general principles or be based on generalisation of quantified experiences. Both routes will be investigated in CALCAS, roughly in **WP3** and **WP5** and broader in **WP7**.

2.3.4 Supply in terms of methods & models

Included are only approaches which at least cover an environmental dimension and at least cover some supply and demand chain elements, making it into a life cycle approach. A private cost based CBA or LCC, for example, covers the supply chain but has no environmental aspects covered and hence is not part of the supply of method & models in CALCAS, in first instance. However, if linked to another method which does cover environmental aspects, like LCA, they enter the analysis in a derived way. The same holds for social aspects, either as goal variables or as models related to social goal variables. As such, they are not included, unless being linked to life cycle based methods and models with an environmental aspects involved.

There are three core questions on how the detailed technology based modelling as in ISO-LCA and related life cycle technology evaluation (LCTA) can be deepened and broadened:

- how to link specific products and technologies to their overall role in society, at a macro level where most sustainability issues reside.
- how to incorporate most relevant mechanisms in a more realistic (i.e., non-linear, location specific, time specific) way, especially economic mechanisms, and more generally how to reckon with the dynamics in society which will influence the product/technology investigated.
- how to link the life cycle system of activities to broader environmental, economic and social mechanisms and values.

Further internal subdivisions in the supply of methods & models we leave untouched in terms of classification or categorisation. Several dimensions have been indicated and formal modelling aspects will be detailed in Chapter 3. Many distinctions based on these dimensions are not mutually exclusive, like systems based on product links or monetary links, which can be combined in hybrid models. Making a systematic classification, or looser categorisation, would be a very cumbersome affair, which might easily exclude relevant and interesting options. So there is no further distinction in scope here, apart as resulting from choices along the several dimension involved.

In section 2.3.2 some main strategic lines for development of methods and models have been sketched: Linking micro systems analysis to the meso and macro level, and incorporating aspects of time in life cycle analysis. These strategic lines are filled in along three tactical directions, not as diverging directions but as views on systematic expansion. These three directions are: the further development of ISO-type LCA; the link to economic sustainability modelling; and the link to physical modelling of economic activities. If they cannot be incorporated in one scientific framework, they become independent directions.

In Chapter three a number of elements for scientific development will be detailed. A main example is how to deal with system boundary definitions vis-à-vis other economic systems. Allocation can be used to cut off systems by partitioning, or by linking to them through substitution and broader market mechanisms. Such broader approaches to allocation could be approached using knowledge from the economic domain of partial equilibrium analysis. Such points will be detailed in Chapter 3. More generally, the work on development in LCA (as ISO-LCA and similar) should be aligned with the ongoing work in the UNEP-SETAC Life Cycle Initiative, see http://www.uneptie.org/pc/sustain/lcinitiative/, and http://lcinitiative.unep.fr/. Where discussions have bogged down, as has happened to the allocation subject in LCA, it is not enough to just restart the discussion again. It is then also needed to draft roadmaps how to overcome the controversies risen.

Though the starting point is at the micro level approach of LCA there is more in the world of life cycle approaches, developing independently from LCA. Three main lines of economics related analysis may be distinguished in parallel to LCA, more and more overlapping with LCA in their domains of application. These are Cost Benefit Analysis (CBA), obligatory in the US in many administrative contexts; Environmental Input Output Analysis (EIOA), as an independent modelling approach and as part of the third approach; applied general equilibrium modelling, customarily abbreviated as CGE (Computable General Equilibrium) models with environmental extensions. As better and more detailed input-output data and models become available and as computing power increases allowing for more detailed elements in CGE modelling, the overlap in domains of application increases.

Similarly, the overlap with substance/materials and energy flow analysis (SFA, MFA, energy analysis, exergy analysis, etc.) is becoming more pregnant, as such models better reflect mass and energy conservation laws, which mostly are ignored in LCA as mass is not specified in any detail (think of a product like a car), allocation procedures, including substitution mechanisms may play havoc and methods for this purpose have not been specified in a specific way. These mass and energy conservation laws are ignored in most economic modelling as well.

There is an urgent need for aligning these different approaches with their different outcomes and to see how far they can be integrated. Starting point for this endeavour is the scope of questions to be answered: Support of sustainability oriented choices on specific products and technologies.

Conclusions on scope in terms of methods and models, 2.3.4

Only those methods and models are included which cover main parts of the life cycle or contribute to such methods and models.

Starting point is LCA, as developing in the ISO-LCA line, broadened in applicability so as also to cover life cycle technology analysis and broadened in scope so as to also include the economic and social goal variables of sustainability.

Results from the working groups of the UNEP-SETAC life cycle initiative form a main input in developing (ISO-type) LCA.
The deepening is along three lines:

- mass and energy conservation principles
- economic mechanisms incorporated or linked
- linking micro level to meso and macro level.

In all cases, the scope is on specifying methods and models to the extent possible now, and to indicate research required for further developments, in relation to demand specifications.

This is the core work in **WP5** and **WP7.**

2.3.5 Supply in terms of practical tools: software & data

For LCA, and increasingly for hybrid LCA, a broad set of software tools and data bases is available, partly from public projects and partly from commercial development. Development or analysis of such tools is not part of CALCAS. However, deepening and broadening of life cycle analysis will require new development in software and data. Software typically will have to be more versatile in covering broadened LCA, and will require substantial new development in deepened LCA. For both, additional data and computational principles are required. For example, in incorporating market mechanisms in steady state modelling, computational requirements are substantially different from the linear homogeneous matrix computations currently used. In terms of data requirements, more processes need to be specified and elasticities of supply and demand are to be known. Empirical data or production functions may form the basis for supply functions. Beyond LCA, software and data bases exist in several domains, for substance and material flow analysis and for input-output analysis, and for the environmental extensions to input output analysis. Also in these domains fast development takes place, which is taken for granted in CALCAS.

Only where the structure of information can be aligned for better integration, the specification or research for improved alignment is part of the work in CALCAS. Also the novel use of available sources for application in life cycle analysis will be part of CALCAS, especially referring to the combined economic and mass specification of flows between economic activities.

Conclusions on scope regarding practical tools, 2.3.5
Development of software and data bases is not part of CALCAS, nor is the survey of what is available.

Indicating requirements on the development of these tools is part of CALCAS however, especially if methods aspects require further research activities. Also, exploring options for making information from other domains available for life cycle analysis is part of the scope. These aspects derive to a large extent from the work in **WP5** and **WP7**.

2.4 Linking demand and supply

The linkage between demand and supply is not self-evident and can become a matter of dispute if the categories involved are not clearly defined. One example is the discussion on attributional and consequential LCA. This distinction may be seen as based on demand requirements. In CALCAS, demand is based on requirements for support on future decision, as opposed to historical analysis. One may want to know how the total of all environmental effects in society is attributed to the full set of products being consumed, for example so as to set priorities in product policy. This is an attributional question. However, when the results are used to draft a policy on changing production or consumption patterns, a consequential analysis needs to be performed. The policy maker then wants to know what the consequence of certain policy options would be. Questions should be based on their purpose. They may be easy or difficult to answer, with one type of method or model or another being more adequate or feasible.

Conversely, when asking a clearly dynamic question, as on the sustainability consequences of introducing large scale biomass-for-energy, the answers may be given by a model based on environmentally extended input-output analysis with specific technologies added, as integrated hybrid analysis, a model as attributional and static as life cycle models do. Such a model is feasible, even beyond current state of the art, and can reckon with all technologies in the chains involved. It still may be poor in terms of the mechanisms incorporated while not covering dynamics in an endogenised way, but it may still be the best available model for now to indicate consequences of choices on bio-energy. It seems worthwhile to investigate if indeed the distinction attributional-consequentional can be reduced to a supply side distinction, and if next it can be framed in terms of the dynamics of the models involved. If incorporating market mechanisms in a comparative equilibrium analysis would count as ‘consequential’ then would be a matter of definition, but not of dispute on content. The underlying modelling specifications as to which mechanisms have been incorporated, and how, can state the nature of modelling much more precisely than the term *consequential*. See also chapter 3 on this point, where in this line of reasoning it is suggested that consequential LCA in a version based on dynamic modelling will step outside the realm of functional unit based LCA. In (more) real life as may be modelled, the consequences of a choice for a technology or product will lead to smaller and larger changes in the volumes and the nature of many other products. Broadened and deepened life cycle analysis may then become very different from current steady state type ISO-LCA.

As questions for decision support can refer to relatively isolated choices with limited consequences, or may involve deep choices on the sustainability of future society, it is clear that there will not be one type of life cycle analysis for answering all questions, if not for theoretical reasons at least for reasons of practical feasibility.

We may envisage a hierarchy of increasing complexity and broadness of questions, with more complex and encompassing models for answering them. The starting point is quite clear. There are simple questions, regarding a limited technology shift, related to one product. An example is the choice between metal or plastic parts in car, with differences in total mass and recycling rates. Good old ISO-LCA, with better standardised allocation procedures, etc. is the appropriate tool for the moment. It allows for easy comparison of options, by disregarding all economic and cultural mechanisms. A first step is to base relations in the model on expected future technologies.

At the other end of the spectrum, there are broad questions, still related to specific technologies. Currently there are many choices being made regarding the resource base for energy production, of which the choice for ethanol as a car fuel is one element. LCA may be a starting point, but it then misses some important consequences. The choice may be to subsidise (by reduced fuel excises/taxes) the use of ethanol based car fuels. Clearly, the energy markets involved will change substantially, with different oil refinery profiles emerging. Also, the effects on global land use will be substantial, leading to shifts towards higher intensity agricultural practices and pressures towards using natural areas for production purposes. Apart from broad environmental consequences there will also be substantial socio-economic consequences. Changes in oil and other energy prices have global distributional effects. Price increases for basic food products are especially heavy for the poor in the world, etc. If sticking to the LCA type functional unit and the steady state model based on linear technology relations, all these relevant effects will be missed. They may be added to the ISO-LCA, involving a mix of models. Some mechanisms may be incorporated in functional unit based LCA, as by reckoning with the shifts in technologies induced. Then a pre-LCA step specifies the processes involved in the LCA. Similarly, results may be placed in a broader context, like indicating land use shifts, depending on the volume of the shift. Clearly, the next step is to consider the size of the change involved, for example "twenty percent ethanol in car driving in the industrialised world". Given the measure of lower excises, the overall demand for car driving will not directly be influenced, only indirectly through higher cost and other taxes to replace the abandoned ones. The answer to the question may still be based on a comparative static analysis of two situations, with specific technologies specifies in the LCA manner. However, there clearly is not just one function involved. Several other products, if not all, will show changes which each may be small but together may be substantial, and overriding the initial change of the technology or product system emerging in ISO-LCA. So ultimately, first quasi-dynamic and then dynamic models are required. Also, such questions with longer term consequences are to be placed in a scenario perspective, as the world cannot be predicted where major choices can be made in society.

It is an essential part of the scope of CALCAS to clarify the demand and supply options and structure, and to indicate how relevant operational models may be developed for actual decision support.

Conclusions on scope for relating demand and supply, 2.4
Questions on the demand side should be framed in a way that assumptions on supply options become clear. Options for supply are to be investigated based on the formulation of demand, and not precluded in demand specification. This is a main challenge in specifying demand with users of current LCA, a main scoping element for the work in **WP6**.
Key scoping point of CALCAS is to clarify the options and structure for demand and supply of information, and to indicate how most relevant operational models may be developed for actual decision support.

2.5 Final conclusions on scope of CALCAS

All scope conclusions drawn above give guidance to the detailing of work plans of **all WPs**, and they need to be implemented by the **WP leaders** in consultation with the partners who are participating in their WP. The detailing will have consequences for the specification of their deliverables as well and possibly for planning of the activities.

3 General modelling framework

This chapter presents a general framework that is supposed to be the implicit basis of many or perhaps even all models of sustainability analysis, at least of those that address the interaction between economic systems and environmental systems. The framework is developed here on the basis of a discussion of theoretical considerations and experiences with a number of concrete models. In the next chapter, a list of concrete models will be categorized along the framework that is central in the present chapter.

This chapter starts with discussing the overall structure of the relation between the economy and the environment, and how models may be used to understand this relationship. In the next sections, we discuss the general modelling principles, and gradually move to more concrete models by introducing simplifications along different lines: the economic domain, the environmental domain, and the spatial and temporal structure of the relationship.

3.1 Interactions between the economy and the environment

In the first section of the discussion on the modelling framework, we give a general overview of considerations that play or may play a role in sustainability analysis. We will discuss the following issues:

- the material basis of production and consumption, i.e. the fact that all functions require a material substrate as the carrier of the service;
- production, consumption, and environmental pressure, introducing the IPAT equation;
- environmental pressure, environmental impact, and other types of impact, introducing the DPSIR framework and broadening the discussion to economic and social aspects;

3.1.1 The material basis of production and consumption

Production theory and consumption have long resided in the realm of economic theory. And economists have had a training that focuses on such aspects as behaviour, price mechanisms and national income. Economic laws were discovered or postulated as providing a basis of the economics of production and consumption. For instance, so-called economic production functions indicate the relationship between the inputs (labour, capital, land, etc.) of a process and its output (products). But the training of economists generally ignored the fact that production and consumption of commodities involves physical objects, such as wheat, steel and cars, and that production and consumption of physical objects must satisfy the laws of physics, chemistry and biology. Worse, many economic laws are in contradiction with the natural laws. They allow producing products with barely any material input, as long as you supply enough labour. The same defect can be seen for consumption: in fact, most products are not consumed, but only changed from a working product into a discarded one. Natural resources, waste and pollution are out of sight for the large majority of economic theories on production and consumption.

Two important exceptions we wish to introduce here are the pioneering work of Robert Ayres and co-workers and that of Nicholas Georgescu-Roegen, both around 1970. The concept of the materials balance principle, or stated in more familiar terms, the law of conservation of mass, has been brought into the discussion around economic production and environmental degradation by

Ayres & Kneese (1969). They constructed a theory and accounting scheme for the mutual relationship between industrial producers, and their relationship with consumers on the basis of the conservation of mass. The other development is connected to the second law of thermodynamics, which Georgescu-Roegen (1971) refers to as "the entropy law". Producers and consumers are not a simple cycle of agents of which the former converts labour into products, and the latter converts products into labour. Instead, an inevitable degradation of quality occurs during this process, one that is deeply rooted in the thermodynamics of irreversible processes.

Both developments have been crucial for understanding how economic activity is connected to environmental degradation, both from the input side of resource depletion as from the output side of waste and pollution. And, as the resource is sometimes referred to as the mother of the waste, the concept of the industrial metabolism was born, introduced by Ayres (1989) as "the energy- and value-yielding processes essential to economic development". It is a modification of the metabolism concept that shows up in biology, ecology and physiology. Thus, the study of the flows of energy and materials through industrial systems has become a crucial view of studying the metabolism of industrial activities involved in production and consumption. It is also crucial in changing this metabolism: from a theoretical perspective one learns about fundamental limits in improving production and consumption, and a comparison of actual efficiencies to maximum efficiencies provides practical guidelines on where large gains can be realised. Here, industrial systems can be interpreted and defined in different ways: from the micro level (individual installations and companies), through the meso level (production-consumptions chains), to the macro level (entire countries or larger).

An analysis of the inflows and outflows of materials and energy at the process level is depicted in Figure 5. It is a combination of the materials balance principle and the entropy law and it indicates the necessity of absorbing raw materials and fuels and of producing by-products. The materials balance principle ensures that these outflows of high entropy must at least in part have a material character, in which case we speak of waste flows or emissions of pollutants.

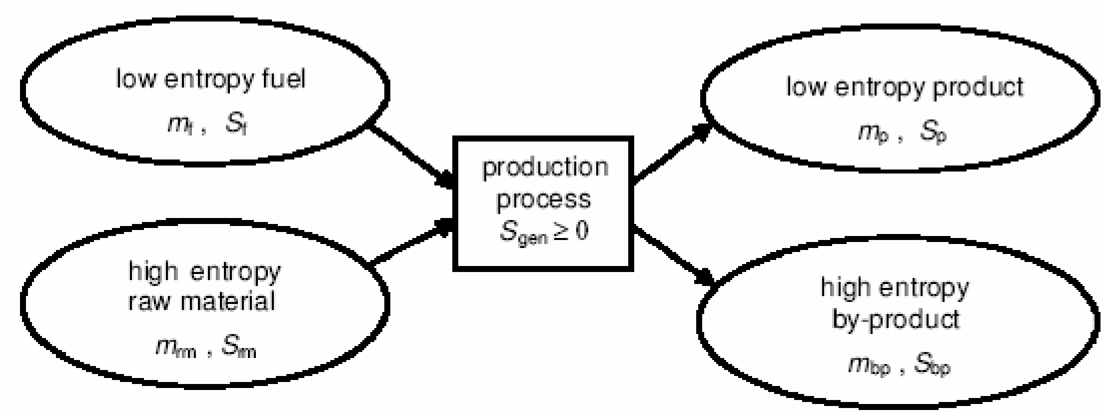


Figure 5**: The thermodynamic structure of an industrial production process in terms of mass (m) and entropy (S). Source: Baumgärtner & de Swaan Arons (2003), p.115.**

Figure 5 has been drafted for a production process, but equally well applies to larger systems, such as installations, plants, companies, supply chains, product chains, countries, and even to the entire world, containing people, ecosystems, and our production systems[9]. As such, it illustrates the scientific foundations of two major problems of production and consumption: resource depletion and waste and pollutants generation. Effectively, it shows that “zero emission” cars or industries (Pauli, 1997) cannot exist.

Another relevant development that can be mentioned in connection with this is that of energy analysis. The purpose of energy analysis is, according to IFIAS (1974), “to establish how much energy is required to make or provide a good or service”. As noted by several authors, the origin of SETAC-LCA lies in energy analysis, where at a certain time the need for accounting for more than “just” the energy was felt.

3.1.2 Production, consumption, and environmental pressure

The famous IPAT equation (Ehrlich & Holdren, 1971), which decomposes environmental impact (I) into the separate effects of population size (P), affluence (A) and technology (T) has been much cited in the field of environmental analysis (Graedel & Allenby, 2003; Chertow, 2000). In its basic form, it expresses the fact that there are three more or less independent variables that determine the level of pollution:

- the pollution per unit of GDP, determined by the technology T;
- the GDP per capita, measured by the affluence A;
- the size of the population, P.

These are combined to form a mathematical expression:

$$I = PAT$$

The assumed independence of the explanatory variables P, A and T and their linear appearance in the equation imply that one can study the separate contributions and effects of changes in these variables to changes in the impact. As such, it provides a valuable framework for categorizing analytical methods for environmental decision-support.

Two remarks are in order. First, the independence of P, A and T, and their linearity in the IPAT equation has been disputed, and more sophisticated forms have been devised (Chertow, 2000). Second, many of the variables, such as environmental impact and technology, are not simple numbers, but many-dimensional concepts. A more elaborate treatment would give a form like

$$\mathbf{i} = \mathbf{TAp}$$

where bold lowercase denotes (column) vectors and bold capital matrices, and where the following definitions have been made:

- **i** represents a vector of *n* environmental pressure types (e.g., releases of CO_2, pesticides) or environmental impact types (e.g., biodiversity, climate change);
- **T** represents a matrix of *n* rows of environmental pressure or impact types and *m* columns of economic activity types (e.g., steel production, railway transport);
- **A** represents a matrix of *m* rows of economic activity types and *l* consumer types;
- **p** represents a vector of *l* consumer types.

[9] Appendix D contains a more elaborated text on the relevance of thermodynamics in understanding life on earth, with a focus on its relevance for understanding production and consumption.

The reversal of the variables from IPAT into ITAP is dictated by the conventions in multiplying matrices. The change of case for I and P comes from the convention of using capital letters for matrices and lowercase letters for vectors.

We will illustrate the use of the IPAT equation in the new form with an example. Suppose we distinguish three consumer types: in developed countries, in transition countries, and in developing countries. Their respective numbers are 1 billion, 2 billion, and 3 billion. Thus, we have for **p** the following:

$$\mathbf{p} = \begin{pmatrix} 1{,}000{,}000{,}000 \\ 2{,}000{,}000{,}000 \\ 3{,}000{,}000{,}000 \end{pmatrix}$$

We distinguish four types of economic activity: housing, food, travel, and entertainment. The affluence matrix **A** could, for instance, be

$$\mathbf{A} = \begin{pmatrix} 10 & 5 & 1 \\ 5 & 4 & 1 \\ 5 & 2 & 1 \\ 20 & 1 & 0 \end{pmatrix}$$

This means the following: a consumer type 1 (those living in developed countries) spend 5 thousand euros in a year on economic activity 2 (food). So, in the cell at the junction of column 1 and row 2 we find the number 5. The connection with the environment is made by the matrix **T**. Suppose we discern 2 environmental pressure types: CO_2 and NO_x. The matrix **T** could have the form

$$\mathbf{T} = \begin{pmatrix} 0{,}1 & 0.2 & 1 & 0 \\ 0.1 & 0 & 0.1 & 0 \end{pmatrix}$$

This means that 1000 Euro of food (column 2) is associated with 0.2 tons of CO_2 (row 1). That's why we find in the cell at the junction of column 2 and row 1 the number 0.2. Putting together all ingredients of the IPAT equation, we find that

$$\mathbf{i} = \begin{pmatrix} 17{,}500{,}000{,}000 \\ 3{,}500{,}000{,}000 \end{pmatrix}$$

This means that, given the specifications of population, affluence and technology, the environmental impact is measured as 17.5 billions of tons of CO_2 and 3.5 billions of tons of NO_x.

The example above must be regarded as an illustration. The numbers are of course hypothetical, but the distinction between three types of consumers, four types of economic activity, and two types of pollutants is also just an example. We will see that many different categorizations are possible and can indeed be found in the literature.

The inevitability of the degradation of our environment in thermodynamic terms does not necessarily mean a loss of environmental quality. The natural environment itself is also a living entity, which on its turn feeds on negative entropy, provided by solar radiation. The living world, and indeed mankind, has been able to live in a harmony for millions or even billions of years. Gradually, this has changed. The IPAT equation distinguishes three directions in which this change has taken place:

- Population: human population size has increased tremendously during the last few centuries. It has more than doubled from 2.5 billion around 1950 to 6 billion around 2000.
- Affluence: In the pre-industrial era, the standard of living was much lower. Most people lived in small houses with few luxury items.
- Technology: Food productivity per acre has increased dramatically. Likewise, the time needed to travel or to deliver a message over 100 km has decreased to an enormous degree. This is all due to developments in technology.

The IPAT equation separates the effects of the combined changes in each of the three directions. This provides an appropriate starting point for the design of a framework for modelling the environmental impacts of economic activity.

Most models concentrate on only one of these dimensions. In particular, functional-unit based LCA concentrates on the technology direction, ignoring the other two directions. That is, LCA is geared along the target of specifying the environmental impact per unit of consumption. It thus seeks to operationalize a formula like

$$\mathbf{i} = \mathbf{Tf}$$

where **f** is the commodity basket that is specified by the functional unit. In Heijungs & Suh (2002, p.19), this formula has been phrased as $\mathbf{g} = \mathbf{\Lambda f}$, where **g** is the inventory vector, $\mathbf{\Lambda}$ is the intensity matrix, and **f** is the final demand vector. The intensity matrix itself has been constructed as a combination of the technology matrix **A** and the intervention matrix **B**: $\mathbf{\Lambda} = \mathbf{BA}^{-1}$. However, to avoid conflicts with the symbols in the IPAT equation, we specify this as

$$\mathbf{T} = \mathbf{T}_B \mathbf{T}_A^{-1}$$

where $\mathbf{T}_B$ is the environmental specification of the technology (like the CO_2 emissions per process or sector), and $\mathbf{T}_A$ is its inter-industry specification (like the electricity requirements per process or sector). In IO-based LCA, we have $\mathbf{\Lambda} = \mathbf{B}(\mathbf{I}-\mathbf{A})^{-1}$, where **I** is the identity matrix, and the term in parentheses with the –1 is the Leontief inverse. We can translate this as

$$\mathbf{T} = \mathbf{T}_B (\mathbf{I} - \mathbf{T}_A)^{-1}$$

Most models of this functional-unit based LCA or E-IOA form are of the form described above. They effectively contain a model that expresses the relationship between a unit amount of product (or sectoral demand) and the environmental impact induced. They do not consider the affluence or population aspects.

There are, however, models in which scenarios on future affluence or future population are included. In such models, the commodity basket **f** is specified as a function of affluence or population, or both. Thus, a specification of

$$\mathbf{f} = \mathbf{Ap}$$

is achieved by means of some form of scenario. Examples of such models are models of economic growth, demography, and models of socio-economic equity development. Some of these models concentrate on one of these aspects only, but other models consider the joint effects of affluence and population. The technology variable, represented by **T**, is then often assumed to be constant. In the famous Club of Rome report, the major issues analysed were of these types: increasing population, increasing affluence, constant technology.

Finally, there are models that combine the technology direction with affluence or population, or with both. For instance, models that focus on decoupling of economy and environment, including those of the Kuznets type, consider simultaneous changes in technology and affluence. Technological optimists, like Julian Simon, on the other hand assume technology to improve in such a way as to allow for a larger population and affluence, with a smaller impact on the environment.

3.1.3 Environmental pressure, environmental impact, and other types of impact

In describing the I of the IPAT equation, we already introduced the distinction between environmental pressure, like CO_2 and pesticides, and environmental impact, like climate change and biodiversity. Within the context of life cycle impact assessment, discussions about environmental mechanisms, cause-effect chains, and midpoint- and endpoint-oriented models have been discussed extensively; see Figure 6 for an example.

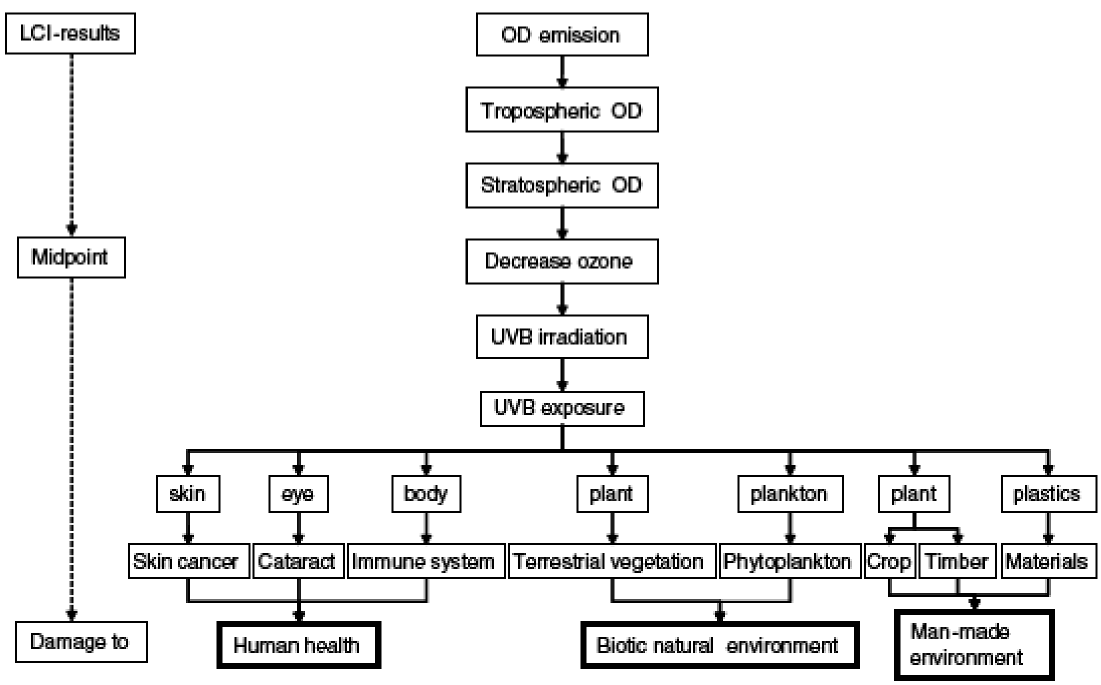


Figure 6**: Example of a cause-effect chain linking environmental pressure (in this case ozone depleting emissions) through midpoints (ozone layer depletion) to endpoints (damage to human health, etc.). Source: Jolliet et al. (2004), p.398.**

The pathways from pressure to impact are complicated and uncertain in many ways. For instance, there may be feedback loops, time lags, non-linear relationships, path dependencies and synergistic or antagonistic effects. Nevertheless, pressures and impacts are in theory equally valid as elements to be modelled in the IPAT-framework. In LCA and LCA-type models, one indeed can distinguish several main schools in describing impacts:

- at the level of the environmental pressure, i.e. at the level of the individual emissions and extractions; this corresponds to an LCI, or an LCA without an impact assessment;
- at the level of midpoint impacts, e.g., covering issues such as climate change, ozone layer depletion, human toxicity, acidification, and abiotic resource depletion;
- at the level of endpoint impacts, e.g., covering issues such as damage to human health, damage to ecosystem health, damage to resource availability, and damage to the man-made environment;
- at the level of a single aggregated index, with weighting factors indicating the environmental concern in terms of policy targets, economic costs, or directly stated societal preferences.

In addition, there are models that formulate results in terms of partial indicators that are supposed the main features of the system. This includes, for instance, indicators of mass throughput, energy input, exergy loss, or area (the ecological footprint).

The relation between pressure and impact is discussed in a more comprehensive framework in terms of the so-called DPSIR-framework (see, e.g., Smeets & Weterings (1999); see Figure 7). This is a framework that considers the relation between economy and environment to be divisible into five aspects:

- the drivers or driving forces (D), e.g., industry, consumers, governments;
- the environmental pressure (P), e.g., emissions, extractions, land use;
- the state of the environment (S), e.g., concentrations of toxics, presence of species;
- the impact (I), e.g., mortality, disappearance of forests;
- the societal response (R), e.g., innovation, taxes, information.

The intermediate S for the state of the environment is an aspect that is often accounted for in multimedia fate and exposure models, whereas the impact itself is indicated using dose-response relationships.

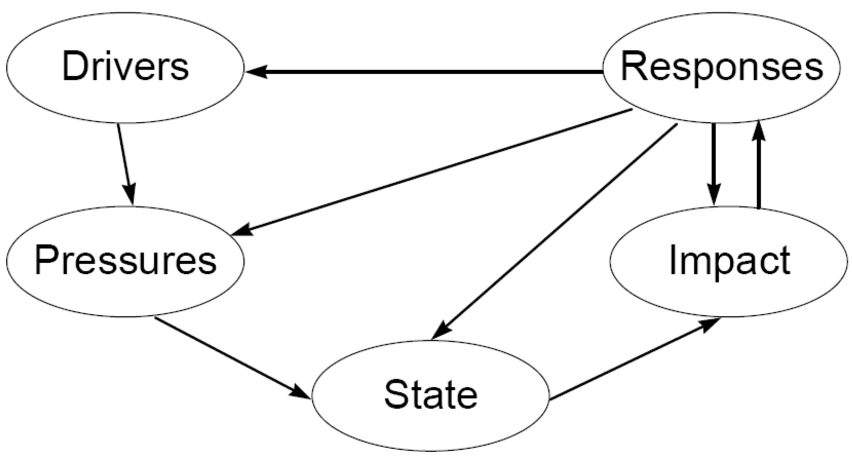


Figure 7**: Overview of the DPSIR framework. Source: Smeets & Weterings (1999), p.6.**

The I in the IPAT equation can now be further specified in terms of pressure, state and impact:

$$\mathbf{i}_S = \mathbf{I}_{fe}\mathbf{i}_P$$

indicating that the impact measured in state $\mathbf{i}_s$ terms is found by applying a fate and exposure matrix $\mathbf{I}_{fe}$ to the impact measured in pressure terms $\mathbf{i}_p$. Likewise, we have

$$\mathbf{i}_m = \mathbf{I}_{dr}\mathbf{i}_s$$

indicating that the impact measured in midpoint impact terms $\mathbf{i}_m$ is found by applying a dose-response matrix $\mathbf{I}_{dr}$ to the impact measured in state terms $\mathbf{i}_s$. These can also be combined into

$$\mathbf{i}_m = \mathbf{I}_{dr}\mathbf{I}_{fe}\mathbf{i}_s = \mathbf{I}_{drfe}\mathbf{i}_p$$

indicating that the impact measured in midpoint impact terms $\mathbf{i}_m$ is found by applying a combined dose-response and fate and exposure matrix $\mathbf{I}_{drfe}$ to the impact measured in pressure terms $\mathbf{i}_s$. The endpoint impact $\mathbf{i}_e$ can be further found by using a damage matrix $\mathbf{I}_d$ applied to a midpoint impact:

$$\mathbf{i}_e = \mathbf{I}_d\mathbf{i}_m$$

or by directly applying an endpoint-oriented method to the impact in pressure terms:

$$\mathbf{i}_e = \mathbf{I}_d\mathbf{I}_{drfe}\mathbf{i}_p$$

Aggregation of the elements within this impact vector may proceed by applying weighting factors $\mathbf{w}_e$ on the endpoints, or $\mathbf{w}_m$ on the midpoints:

$$i_{am} = \mathbf{w}_m\mathbf{i}_m$$

which yields an aggregated single indicator at the midpoint level i_{am}, or

$$i_{ae} = \mathbf{w}_e\mathbf{i}_e$$

which yields an aggregated single indicator at the endpoint level i_{aem}.

Although the IPAT equation was originally conceived to express a relation between production and consumption on the one hand and the environment on the other hand, there is no reason to restrict the framework to environmental impacts alone. Especially after having generalized the impact I into a vector of impacts $\mathbf{i}$, it is possible to add additional entries for social or economic impacts. Thus, we can regard the impact vector as a partitioned vector:

$$\mathbf{i} = \begin{pmatrix} \mathbf{i}_{env} \\ \hdashline \mathbf{i}_{soc} \\ \hdashline \mathbf{i}_{econ} \end{pmatrix}$$

In most models for environmental analysis, like ISO-LCA, the environmental dimension is present, but the other two dimensions are absent. Other methods, like cost-benefit analysis, concentrate on one of the other dimensions. Some methods address two of these dimensions. An eco-efficiency approach, for instance, calculates one (or more) environmental scores and one (or more) economic scores, and integrates these into a single eco-efficiency indicator:

$$i = f(\mathbf{i}_{env}, \mathbf{i}_{econ})$$

where *f*(...) indicates a certain function, e.g. a ratio of weighted summations.

There are also approaches, such as in ExternE, that translate an environmental indicator into an economic one, for instance using shadow prices on the basis of the willingness-to-pay. Thus,

$$i_{econ} = \mathbf{w}_{ee}\mathbf{i}_{env}$$

where $\mathbf{w}_{ee}$ is a vector of (shadow) prices. Finally, we mention approaches that convert economic and social indicators into environmental indicators. Norris (2006), for instance, uses input-output tables to estimate changes in economic activity as a result of changes in product demand, and relates this to changes in mortality through empirical relationships between income and health.

$$i_{env} = \mathbf{w}_{ee}\mathbf{i}_{econ}$$

where $\mathbf{w}_{ee}$ now expresses the relationship between different types of economic productivity and human health.

Concluding so far, we have been discussing models that calculate some form of impacts, distinguishing the following aspects:

- pressure, state and impact;
- midpoints, endpoints and weighted single indicators;
- environmental, economic and social dimensions.

In addition, we have briefly alluded to models that use proxy indicators, such as the ecological footprint.

A central focus element for developing environmental analysis for sustainability will be on consistency. As a first step, environmental aspects covered will be distinguished as to intervention level, midpoint level, and endpoint level. For example, biodiversity as one prime environmental aspect in sustainability evaluation first will be placed in the causal chains involved, comprising inter alia biotic extractions, land use, climate change, eco-toxic emissions, acidification and nutrification. Biodiversity itself contributes to ecosystem stability and ecosystem functions. It then is easily inconsistent to analyse product systems as to their score on both climate change and biodiversity, as climate change is a main constituting factor for biodiversity. The structure and consistency analysis is part of CALCAS, possibly indicating requirements on further research.

Another focus is the relation between the definition and treatment of the indicator categories and multi-criteria decision theory. In Section 2.2.2, some forms of weighting were introduced in relation to governance. There is also a scientific framework for organizing information in the context of decision-making. Decision theory, and in particular the various forms of multi-criteria analysis can help the sustainability analysis to construct a more solid foundation (Hertwich et al., 2000).

Some aspects not yet fitting in the inventory-environmental effects framework require special attention, being relevant and not having a systematic place in the analysis. One salient example is risks, as calamities resulting from unplanned but to some extent predictable deviations in industrial operations. Partly, such aspects may be covered in the specification of economic activities, like traffic accidents in truck transport, linked to adequate mechanisms like casualties. Partly, they require other environmental effect routes, like for the fall-out after the Chernobyl-like accidents.[10] Partly, they may be treated as additions to inventory specifications, like casualties and emissions from fire accidents. One central question here is how to structure such surely relevant effects, either incorporating them in a broad definition of environmental effects, or giving them a place as a separate category of damages, or as damages which may occur through non-environmental mechanisms, as social damages. See Appendix C for an example on the treatment of fire accidents.

[10] The socio-political risks of nuclear proliferation and terrorism might be part of social aspects, next to environmental ones. Such lines will not be worked out in CALCAS in any detail.

3.1.4 Models for environmental decision-support

Every model for environmental decision-support is concerned with a number of simplifications and/or restrictions. For instance, in some models, technology is assumed to be constant, while in other models, the affluence is assumed to increase at the same rate as it has done in the past.

CALCAS focuses primarily on LCA, and so does this document. This means, that we will now concentrate on the mainstream LCA, the ISO-LCA. The ISO standards for LCA provide general principles, but do not give their scientific foundations, nor do they give a detailed elaboration. In the next chapters, we will discuss the foundations, framework and elaboration of ISO-LCA, as provided by some other important documents.

3.2 General modelling principles

In all models, we find a number of things in common. General systems theory presents an approach to discuss models in a unified way (Von Bertalanffy, 1968). Important structural aspects of models are the following:

- the distinction between a system and its environment;
- the internal structure of a system in terms of its components;
- the relationship between the components;
- the relationship between the system and its environment;

In the following, we will discuss the general structure of model system. In doing so, we will often use ISO-LCA as the prime example to illustrate the various notions. We will in some cases use IOA to contrast and complement this. We will first, however, address an issue that relates to the purpose of the model.

3.2.1 The purpose of models for sustainability analysis

Chapter 2 has introduced the distinction between the demand of tools and the supply of tools. Decision-makers want to be informed, and scientists develop information tools and calculate indicators. In the process of choosing or developing the right tool for a concrete decision, an issue that shows up again and again (Heijungs, 1997; Frischknecht, 1998; Weidema et al., 1999; Tillman, 2000; Curran et al., 2001; Weidema, 2001; Werner & Scholz, 2002; Guinée et al., 2002; Ekvall & Weidema, 2004; Ekvall et al., 2005; Ekvall & Andrae, 2006) is the distinction between consequential and attributional LCA; see also Section 2.4. A large variety of words has been coined to refer to these terms: prospective vs. retrospective, change-oriented vs. accounting, etc. Quoting from Ekvall & Andrae (2006, p.345):

- Attributional methodology for life cycle inventory analysis (LCI) aims at describing environmentally relevant physical flows to and from a life cycle and its subsystems.
- In contrast, consequential LCI methodology aims at describing how the environmentally relevant physical flows to and from the technosphere will change in response to possible changes made within the life cycle.

The choice between attributional and consequential models (LCA, LCI, or more general) may have many consequences for the modelling principles, for instance the system boundaries, the types of data to be collected (e.g., average or marginal), allocation calculation methods and the impact assessment principles and data.

The emergence of the distinction between attributional and consequential models has been theoretical mainly, although some practical implementations have been published (e.g., Weidema et al., 1999; Ekvall & Andrae, 2006). There are good reasons for the lag of the practice: most LCI databases, for instance, provide average data and most impact assessment factors are a mix of average and marginal factors, so that all attempts for being pure are restricted to small exercises.

The distinction between attributional and consequential models has been motivated by considerations of demand. It has been argued that decision-makers are concerned with making choices, and that therefore a consequential model is most appropriate. But it has also been suggested that a decision-maker has first to know where to prioritize, and that this involves the identification of major contributors, a clear question of attribution. In principle, therefore, a demand for both modes of LCA is conceivable.

The CALCAS project will have to investigate:

- to what extent the distinction between attributional and consequential models can be linked to the demand for sustainability information;
- what the differences are in the modelling strategy with respect to system boundaries, allocation, data, impact assessment, etc.
- what the differences are in the practical sense of availability of data, computational tools, etc.

3.2.2 The distinction between a system and its environment

In ISO-LCA, the flow diagram (Figure 8) is a visual means that helps to clarify the choice of the system and its environment. One might argue that the system is in this case the product life cycle, and that the system's environment is the rest of the universe, in particular the rest of the economy and what we usually call "the natural environment". However, that is not correct. In systems theory, the system environment is supposed to be very large; so large in fact that it is not affected by the system. The environment is an unlimited source and sink of materials and energy, hence the environment is unchangeable. That is clearly not the case in LCA, where the prime purpose is to model changes in the environment, like climate change or acidification, as a result of the functioning of the product system.

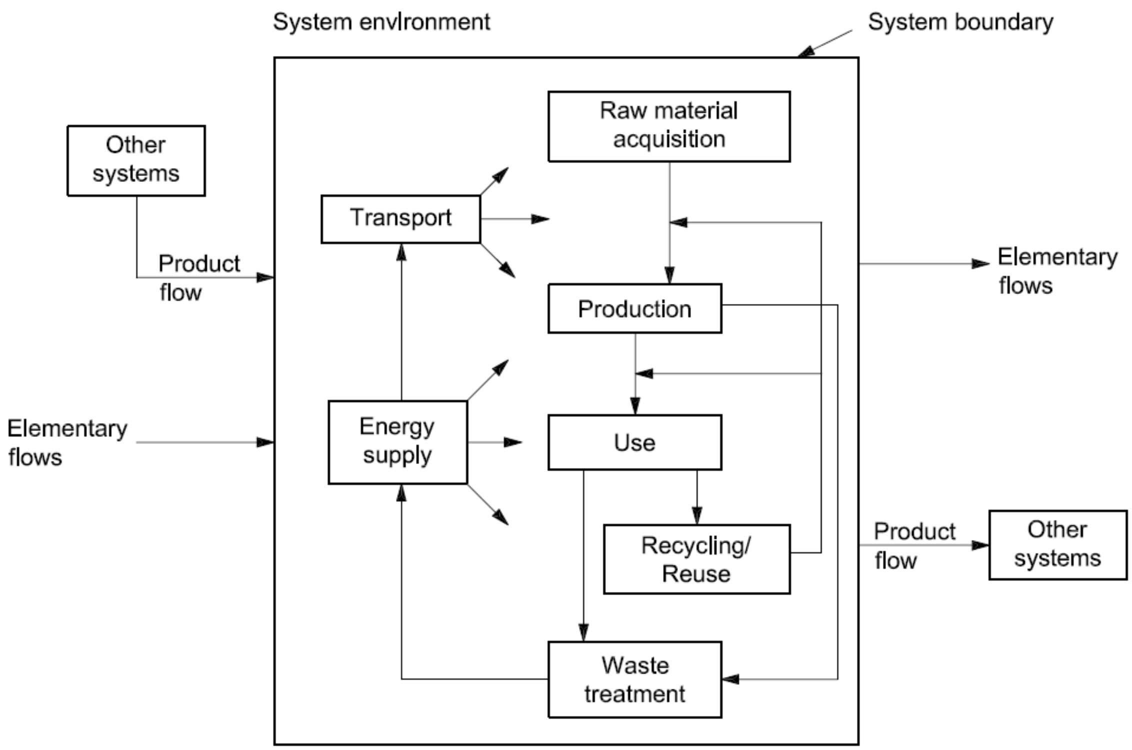


Figure 8**: Example of a flow diagram in ISO-LCA. Source: ISO 14040 (2006), p.10.**

The correct view is that in LCA the product system and the natural environment together form the system, and that the rest of the economy and the rest of the universe (e.g., the sun) form the system environment. The product system can be said to be a subsystem, and so is the natural environment. The wide systems view expressed here has some implications: both the product system and the natural environment are so complex that an experimental verification of the results obtained by LCA becomes practically impossible. However, as has been pointed out (Oreskes et al., 1994), verification and validation of numerical models is impossible, and they can only be evaluated in relative terms.

A term that one frequently encounters with respect to demarcating the system and the environment is that of the system boundary. The issue of system boundaries is critical in LCA, but it equally critical for other models.

In IOA, the system is often a national economy, and its environment is the rest of the world's economy and the natural environment. In environmentally extended IOA, or EIOA, the natural environment is part of the system, together with the national economy.

3.2.3 The internal structure of a system in terms of its components

ISO-LCA concentrates on unit processes as the basic components of the economic subsystem. A unit process is defined as the "smallest element considered in the life cycle inventory analysis for which input and output data are quantified" (ISO 14040, 2006, p.5). In present-day LCAs, these are typically activities like electricity production, steel rolling, product assembly, transportation by truck, use of a refrigerator, and recycling of paper. In IOA, the components are most often economic sectors, like agriculture, chemical industry, and power plants. That is, the aggregation level of the components is in IOA typically higher than in LCA. Notice, however, that there are various aggregation levels possible in both IOA and LCA.

In LCA, the economic subsystem's components are usually indicated by boxes in a flow diagram (Figure 8).

The second subsystem in LCA is the environment. The components considered here are the environmental compartments considered. These may be the classical compartments air, water and soil. To an increasing extent, a finer subdivision of compartments takes place, along various directions:

- compartments are being subdivided into more homogeneous compartments; for instance, the water compartment is subdivided into lakes, rivers, seas, and groundwater;
- compartments are being subdivided along lines that relate to differences in use; for instance, the soil compartment is subdivided into agricultural soil, industrial soil, and natural soil;
- compartments are being subdivided into more regionalized compartments; for instance, the air compartment is subdivided into European air, Asian air, African air, etc;
- compartments are being subdivided along lines that relate to differences in target species; for instance, the air compartment is subdivided into high-population density air, low-population density air and the stratosphere.

Organisms themselves can also be considered as components of the environmental subsystem: through processes like bio-magnification they may help to determine the pathways of pollutants in the environment. Considering the resource side of the environment, organisms also play a role as productive agents: fish are produced by parent fish, and grow by the consumption of other fish and other organisms.

3.2.4 The relationship between the components

The components in a system influence one another. We first discuss the relationships between the components of the economic subsystem.

In a flow diagram of LCA, these relationships are typically visualised by drawing arrows between the components, at least for the subsystem that represents the product system. These are only visualisations, but they represent in the LCA model quantitative connections. In ISO-LCA, these quantitative relationships are very simple. For instance, they are linear homogeneous, which means that two times as much electricity means two times as much fuel. In more sophisticated models, such relationships may be modelled more realistically. Another example of the simplification is that there is no time information incorporated in these relationships.

The choice of system boundaries and the modelling of the relationship between the components within the economic subsystem also relate to the problem of allocation, i.e., the partitioning of the environmental burdens of a technological activity among the life cycles in which the activity fulfils a function. The partitioning becomes a methodological problem when, for example, the activity results in several products that are used in different life cycles, or when a material, through recycling, is utilised in more than one life cycle. Problems associated with allocation caused the most debate during the development of the international standard for LCI (Anonymous, 2006b). The allocation problems have also been the topic of many scientific papers and several PhD theses (e.g. Huppes, 1993; Azapagic, 1996; Schneider, 1996; Heijungs, 1997; Frischknecht, 1998; Karlsson, 1998; Ekvall, 1999; Trinius 1999).

The relations between the components in the environmental subsystem are usually not visualised in LCA. They are, however, typically addressed by simple models, in the sense as defined above. For instance, the relation between an economic subsystem that emits greenhouse gases and the component that represents climate change is usually modelled by a straightforward application of global warming potentials (GWPs), even though these GWPs themselves have been derived from more complicated models, involving non-linear relationships and time lags.

The components exert an influence on each other by means of links. In ISO-LCA, these links are the exchanges between the components. The links between the components of the economic subsystem are the flows of products, materials, energy, services, and waste. The links between the components of the environmental subsystem are chemicals (pollutants) and resources (biotic and abiotic).

The links in LCA can be expressed in various ways. Typically, physical flows, like products, materials, energy, chemicals form the link, and they do so in physical terms: pieces, kg, MJ, Bq, etc. In EIOA, the links are typically unspecified sectoral outputs (like "agricultural output"), expressed in monetary terms: Euro, dollar, etc. Both approaches have their strong and weak points. Monetary connections are easier to obtain, as companies and tax offices have a quite detailed knowledge on the transactions between companies. However, not all connections have monetary tags, so that they fall outside the statistics and can be forgotten easily. In particular, waste and releases to the environmental suffer from this. An interesting third point of view is taken by material flow analysis, substance flow analysis and energy analysis, where the focus is on a mass or energetic link. Thus, a refrigerator is accounted in terms of its content of a certain material or energy. This provides a way to work use physical conservation laws (of energy and mass) as a data consistency check.

When discussing the allocation problem and related questions on system boundaries, it is useful to distinguish between attributional and consequential LCA (see 2.4 and 3.2.1). An attributional LCA typically includes, and is limited to, the whole life cycle from cradle to grave. Allocation problems are typically solved through partitioning of environmental burdens in proportion to some property of the products: the economic value, mass, volume, etc. (Tillman 2000). The system boundaries in a consequential LCA, in turn, are defined to include the activities contributing to the environmental consequences of a change, regardless of whether these are within or outside the cradle-to-grave system of the product investigated. Allocation problems are often avoided by expanding the system boundaries to include affected processes outside the cradle-to-grave system (Tillman 2000).

3.2.5 The relationship between the system and its environment

In thermodynamics and in general system theory, it is customary to distinguish three types of system:[11]

- open systems, that allow the transfer of matter and energy between the system and the environment;
- closed systems, that only allow the transfer of energy between the system and the environment;
- isolated systems, that do not allow any transfer between the system and the environment.

In most models for supporting sustainability decisions, the starting point is one of a closed system. Solar energy is assumed to be available as an unlimited inflow, and waste heat may be disposed to space, to the extent that it is not being kept within by the atmosphere. Some models are more open, however. They assume that natural resources are available without limits. The usual paradigm in sustainability analysis, however, is one of depletable resources. In fact, this means that the natural resources are considered as a part of the system, usually within the environmental subsystem, or in a separate geological subsystem.

3.3 Issues of economic mechanisms

Models that model the relation between economic activities, such as production and consumption, and the environment, invariably contain information on economic mechanisms. This can be done at various levels of sophistication, and in various ways. In this section, we will address some basic mechanisms that can be of interest in models.

First, however, we have to make clear what we mean with an economic mechanism. For that, we will take a phenomenological point of view. An economic mechanism is a causal relationship that connects the level of two economic activities. Obviously, the economic activity of watching TV is connected to the economic activity of producing electricity. One could argue that this is a physical mechanism: TVs use electricity. But as we consider TV use and electricity production as an economic process, we will conceive their causal[12] connection as an economic mechanism, albeit with a physical counterpart.

The arena of economic mechanisms is much wider. Using a TV also ‘causes’ the prior production of the TV, and it likewise will yield a broken TV after a couple of years, causing[13] the need of waste treatment activities. Associated with the use of a TV is a whole series of broadcasting activities, requiring studios, electricity, costumes, and so on. Many TV users are subscribed to a programme guide, which needs to be produced, distributed, and discarded after

[11] See, e.g., Adkins (1983) for a thermodynamic treatment, and Von Bertalanffy (1968) for a systems theoretic treatment. The latter lumps, by the way, closed and isolated systems: “closed systems, i.e., systems which are considered to be isolated from their environment” (Von Bertalanffy, 1968, p.39).

[12] Notice that the term ‘causal’ may be considered to be not fully appropriate in the present context. Normally, we mean by a causal relation between A and B in the sense that A causes B that A precedes B. In that sense, using a TV cannot cause the production of electricity. But producing electricity cannot be the cause of the use of the TV either. We should understand the term here in the sense of a *conditio sine qua non*.

[13] Again, we have to moderate the meaning of the term ‘cause’. Waste treatment of a broken TV is not a *conditio sine qua non* for the use of a TV. It is not possible to watch a TV which has not been produced, but it is entirely possible to watch a TV which will never be treated after its end of life.

use. In a different direction, we know that TVs are used in a specific personal surrounding, for instance with the person watching seated on a leather sofa, eating popcorn meanwhile, and drinking a coke. In that sense, the use of a TV causes a whole array of economic activities that relate to production of food, drinks and furniture, and its waste processing. Still more remote is the connection between watching a commercial on TV and buying the thing that was being advertised. Or between watching a documentary on Easter Island and booking a holiday trip to it one year later.

Of course, some of these links will be more essential than others. Without a TV and without electricity, you cannot use the TV. Without the sofa, you can, although it is less convenient. The point is, however, that these relationships are present to some extent.

The conclusion of these reflections is that there are many economic mechanisms of a varied nature. We can try to categorize some main groups:

- There are technical and physical 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 legal relationships: using a TV will eventually lead to a discarded TV, which is supposed to be treated according to the laws.

In ISO-LCA, the first and the third group are in general covered to quite some extent. 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. The second group is completely left out of LCA in most cases. Some behavioural elements, however, do show up in some LCAs. For instance, a functional unit may take care of the user's behaviour with respect to the number of hours of use and the number of hours of stand-by mode. Use of the substitution method for allocating co-production processes, leading to 'avoided burdens' is also often based on assumptions of the economics of avoided production. Another behavioural mechanism that is sometimes accounted for is the rebound effect.

As indicated above, a consequential LCA (CLCA) should ideally include all processes, within and outside the life cycle, to the extent that they are expected to be affected by a decision or a decision-maker. The system boundaries and input data will depend on the purpose of the CLCA. If the purpose is to assess a specific decision, or a set of specific options, the CLCA model should include all processes to the extent that they are expected to be affected by the decision. If the purpose of the CLCA is to generate ideas for decisions, identify key issues, or to increase the level of knowledge in general, the inventory model should include all processes to the extent that they can be affected by the specific set of decision-makers that is to be informed by the LCA results. For simplicity this set of decision-makers are in the following denoted "the decision-maker".

A change in the demand by a specific decision-maker typically causes changes that are small enough to be approximated as marginal effects on the production of bulk materials (e.g., steel, aluminium, polyethylene), energy carriers (e.g., electricity, heavy fuel oil, petrol), and services (e.g., waste management), for which total production volume is very high. Marginal effects should, ideally, be modelled using marginal data that, by definition, reflect the environmental burdens of the technology affected by a marginal change (Weidema 1993). In some cases, a process can be substantially affected by a decision or a decision-maker. Such effects should be modelled using incremental data that are likely to depend on the scale of change (Azapagic & Clift 1999).

The marginal technologies are often identified using static models of the variable. This requires that the LCA practitioners identify for what technologies the production is constrained to a specific production volume or to a specific production growth (Weidema et al. 1999). Constraints can be physical, political, or economic. In the energy sector, physical constraints include available potential energy in rivers etc. Political constraints include, for example, bans against further expansion of hydropower or political targets regarding CO2 emissions. Economic constraints can include the quantity of biofuel available as by-products from forestry, sawmills and pulp mills. What we consider to be the marginal production can depend heavily on what constraints we choose to regard as fixed, and it is unclear if an objective method for identifying fixed constraints can be found.

The marginal technologies can also be analysed using dynamic optimising models (Mattsson et al. 2003). The latter approach give a more complete description of the consequences, because it takes into account effects on the utilisation of existing production facilities as well as effects on investments in new production facilities; however, the results from the dynamic optimising models can be complex and depend heavily on assumptions regarding uncertain boundary conditions, future fuel prices etc. (Mattsson et al. 2003).

The sphere of influence of a decision-maker includes not only the production of upstream products. It also includes, for example, the use of the upstream processes in other life cycles, the waste management of other products, and the level of economic activity in the society (see Table 3). If a manufacturer takes actions to reduce her electricity consumption, the reduced electricity demand of the manufacturer will contribute to keeping the electricity price down. This may result in an increase in the electricity demand of other consumers, offsetting part of the energy savings originally made.

Table 3: **Example of types of consequences of a decision.**

Type of consequence	Example: Effect of profitable electricity efficiency investment	Modelling method
Marginal production	Reduced natural-gas power production	Dynamic, optimising models
Demand of other consumers	Increased through price reduction	Partial equilibrium models
Economic activity	Increased through money savings	General equilibrium models
Technological development	Increased through additional	
accumulated experience	Models with experience curves	
Knowledge and values	Increased knowledge and inspiration	Marketing models?

through good example

To the extent that the total electricity production is reduced by the actions of the manufacturer, this can affect the quantity of natural gas used for electricity production. This will contribute to keeping the gas price down, which may result in an increased use of natural gas for the production of plastics. The plastics can replace other materials in certain functions, changing the balance between supply and demand for these materials, and so on. Again, the chains of potential causes and effects do not seem to have an end.

Impacts on the balance between supply and demand for a specific good can be analysed using partial equilibrium models that describe the relation between supply and demand through the use of the concept price elasticity (Friedman 1976). These aspects of CLCA methodology are presented in some detail by Weidema (2003) and by Ekvall & Weidema (2004). To describe chains of cause-and-effects like the one discussed above, several partial equilibrium models may have to be linked to each other. A problem, in this context, is that the uncertainty can be large in a single partial equilibrium model (Ekvall 2000). In a system of interlinked equilibrium models, the uncertainty is likely to be very large. When yet another equilibrium model is added to such a system, the additional uncertainty can easily be larger than the additional information obtained.

Returning to Table 3, net energy savings and reduced electricity price means that less money is spent on electricity in the society. The money saved can be used for other activities that, most likely, use electricity as well as other energy and materials. This rebound effect also offsets part of the energy savings originally made. Impacts on economic activity can be analysed using general equilibrium models that describe the connection between capital, labour and resources in the economy (Ibenholt 2002).

However, buying equipment for improving electricity efficiency will add to the experience of producing this equipment. This is likely to contribute to reducing the manufacturing cost of the equipment (Wright 1936). Increased experience from manufacturing is also likely to improve the technological performance of the equipment (Claeson 2000). The improved technology and reduced manufacturing costs both make the equipment easier to sell to other manufacturers. In this sense, the investment made by the first manufacturer makes it more likely that other manufacturers will make similar investments. This is a positive feedback mechanism, which means that the electricity savings resulting from the investment can be greater than the savings originally made (Sandén & Karlström 2007). Impacts on technological development can be analysed using systems models that include experience curves (Mattsson 1997).

If knowledge of the actions taken by the manufacturer is spread, other manufacturers may also be more prone to take similar actions because they become better informed about the more energy-efficient options and because they may become inspired to focus more on energy-efficiency. The impact on knowledge and values is a potentially positive feedback mechanism that can possibly be analysed using models of marketing experts.

It is apparent that a more accurate modelling of the consequences of decisions requires a series of economic models and concepts to be integrated into the models for environmental systems analysis (Ekvall 2003). The life cycle inventory modelling has, in principle, a clear target in this case: to include all processes, within and outside the life cycle, to the extent that they are affected by a decision or a decision-maker. However, the future is inherently uncertain and a CLCA practitioner can, in practice, only aim at describing the foreseeable consequences. The CLCA practitioner needs to decide what type of causal chains can be foreseen (cf. Table 3.3.1). She also needs to decide how far each causal chain should be traced. When the uncertainties grow too large, further expansion of the system investigated yields no additional knowledge.

A complication in terminology is that the aim to describe consequences of a decision might result in a methodology where the cradle-to-grave-perspective looses much of its relevance. Actions taken to reduce electricity demand at manufacturing does not necessarily have a discernible effect on the extraction of natural gas, the cradle of the marginal electricity in this case. The aim to describe consequences might also result in a methodology where the functional unit is no longer relevant, because the decision can affect the functional output of the system. The increased use of electricity by other consumers in Table 3.3.1, and the possible increase in polymer production, can generate additional functions. The rebound effects described by general equilibrium models also mean that the functional output of the economy is affected. The fact that a consequential study does not always describe alternative ways to deliver an equivalent function makes it fundamentally different from traditional LCA. It is not obvious that a study without cradle-to-grave-perspective and/or a fixed function measured in functional units should be called an LCA at all.

3.4 Issues of time and space

In models for sustainability analysis, like in many other models, we can discern many characteristics that relate to the treatment of time and space (see, e.g., Hofstetter, 1998, p.24-26). Some of the issues are the following:

- the representativeness of the model, e.g., assessing the environmental aspects of a product on the German market in 2005;
- the degree to which results of the model are specified in time and space, either as a continuous function of time and space, or as a time series or with geographical labels (e.g., emission of NOx in Spring 2003 in Sicily);
- the degree to which stressors or impacts that occur at other places or other times are treated differently, for instance with different population density numbers or with a time-preference factor (discounting).

Of course, there are more issues that relate in some way to time and space. For instance, models may contain activities related to transport (displacements in space) or storage (displacement in time), with their associated impacts. These activities, however, are considered here to be part of the system that models the economic mechanisms; see Section 3.3.

In general, activities, emissions, impact and other events happen at a specific place and at a specific time. All models that somehow deal with more than one activity, emission, impact, etc. thus have to consider how to treat differences in place and time. Some basic options are:

- to ignore such specifications, for instance simply adding an emission of NOx in Spring 2003 in Sicily and an emission of NOx in July 2004 in London into an emission of NOx at an unspecified time and an unspecified place;

- to maintain such specification, for instance keeping separate the two emissions of NOx in the example above;
- to use such specifications for a dedicated aggregation; see below for more detail.

A well-known example of a dedicated aggregation is the use of a time-preference factor, also referred to as discounting. Impacts in the future are often regarded to be less important than impacts right now. The net present value of an impact may be calculated by applying a discount rate, and it may then be added to impacts at other moments in time. The act of introducing a time preference is disputed, especially in the context of intergenerational sustainability (Hellweg et al., 2003; Sumaila & Walters, 2003). However, it is used in certain cases, and it provides an important mechanism to aggregate impacts at different times. A more crude form is to apply a time horizon, say of 100 years, where all impacts within this time frame are aggregated, and all impacts at later times are excluded. For dedicated aggregation of spatially differentiated impacts, we may refer to models that account for differences in soil conditions, vegetation, population density, etc. at different places.

The basis of any spatial or temporal differentiation is the recognition of the fact that activities are separated in space and time. If I decide to buy a car today in Berlin, this will affect many actors in the future. For instance, I may use the car 213 days later in Madrid, creating pollution, and buying gasoline. The degree to which a model will be able to deal with a spatial or temporal differentiation depends on the entire set-up of the model and the way relationships between activities have been introduced. Especially the treatment of time turns out to be important. Equilibrium models, for instance, basically ignore changes in time. If something changes as a result of a decision, the change will be introduced immediately, and an assessment of the consequences of such a change will be phrased in terms of comparing two equilibrium situations: a comparative steady-state model.

On the other hand, evolutionary models allow for a modelling of changes in the course of time. We can study how changes will propagate in different parts of the system as a function of time. Two variants that may be seen are models that work with discreet time steps, and models that incorporate a continuous time variable. The first of these may deliver time series, e.g., emissions in year 1, in year 2, etc. The second one may describe emissions as a continuous function of time. Terminology is sometimes confusing here. The word “dynamic” derives from the Greek word for force or power, and is in scientific use in the context of classical mechanics to indicate the results of forces (such as gravitation) that act on bodies (such as planets).[14] As forces lead to changes in time, the word “dynamic” has received a wider use, indicating anything that has to do with changes in time. Newtonian mechanics deals with (continuous) differential equations, allowing the description of systems at any time. However, the term “dynamic” has also become increasingly popular to denote changes that are measured as time series. The consequence is that what is a dynamic model to one is not so to another one.

The last decade, many researchers have developed principles of and elaborations of spatially differentiated characterisation models and factors that can be connected to a spatially differentiated inventory table. Examples can be found in Potting & Hauschild (1997), Krewitt et al. (1998), Potting et al. (1998), Potting (2000), Huijbregts et al. (2000), Moriguchi & Terazono

[14] See, for instance, Leibniz’ *Specimen Dynamicum* of 1695.

(2000), Bare et al. (2002), Pennington et al. (2004), Basset-Mens et al. (2006), Hauschild et al. (2006) and Bellekom et al. (2006).

3.5 Combined models

Different types of models can be combined to achieve a more comprehensive analysis of the environmental, economic or social aspects of a life cycle or decision. As an example, hybrid analysis is a combination of the process LCA and environmentally extended input-output analysis.[15] However, the concept of hybrid analysis is a much broader concept (Udo de Haes et al., 2004).

There are two fundamentally different approaches to linking models. Soft linking means that the results from one model are manually fed into the other. A number of iterations can be performed were both models are manually tuned to be consistent with each other. Hard linking means that the models are integrated to become, in essence, a single computer model. When a hybrid analysis is conducted with an LCA model that includes input/output tables, it is a case of hard linking.

According to Wene (1996), soft linking is the most practical starting point. Keeping the two models separate increases transparency; and the iterations in the soft linking procedure contribute to the learning process. This means that more can be learned from soft linking. Hard linking, on the other hand, makes it possible to produce more results, since the automatic calculations are quicker. For this reason, Wene argues, hard linking is the preferred end result in the development of models. Hard linking also produces a unique and completely consistent solution, where the iterations of soft linking depend on subjective choices and may result in solutions that are not fully consistent.

A special case of soft linking is the toolbox approach (see, e.g., Wrisberg et al, 2002; Ekvall et al., 2005), where the models are deliberately kept separate to allow for a methodological flexibility. Different models are selected and soft linked depending on the need of the particular case study. The toolbox procedure relies on the recognition that different approaches are required for modelling different types of causal mechanisms (see Table 3), and that no single person is an expert on all approaches. For this reason a toolbox approach may require not only a combination of models but also a combination of experts.

Combining models or aspects from models is a gradual thing. Even ISO-LCA, although referred to as LCA, contains some aspects of other models. Many characterisation factors, for instance, have been derived from other models, like for assessing climate, toxicity and acidification. And characterisation factors that have been derived for LCA have been used for other models, such as substance flow analysis, thus leading to "combining SFA and LCA" (Tukker et al., 1997).

Another issue in combining models is not the linking, either soft or hard, of the models where the output of one is to input of the other, but the combined consideration of their outputs. For instance, when one has a result of an environmental assessment and one of an economic

[15] A note on terminology: some writers distinguish LCA and EIOA, and refer to the combination as hybrid analysis. Other writers distinguish process-LCA and EIO-LCA, and use the term hybrid LCA for the combination.

assessment for a number of options (e.g., alternative products), there are at least three ways to combine these:

- by making a two-dimensional picture with one axis representing the economic and the other the environmental variable, and by plotting all options as points in this space;
- by forming a ratio of the economic and the environmental variable of every option, thus calculating an eco-efficiency indicator;
- by adding the economic and the environmental variable with a weighting between them that accounts for the trade-off between economy and environment. Three main schools are to translate ecological terms into economic terms (by using external costs, see, e.g., Krewitt et al, 1999), to translate economic terms into ecological terms (or in health terms, see. e.g., Norris et al., 2006), or to weight economy and environment in a multi-criteria analysis (see, e.g., Balteiro, 2004).

3.6 Simplified models

ISO-LCA has on several occasions been criticized for being difficult and impractical. The theoretical concepts include difficult terms and ideas, like reference flow, system expansion and category indicator, terms that are not trivial and that require a basic training in LCA. The practice of LCA, moreover, requires the collection of a lot of data on processes, products, and substances, and for which choices must be made with respect to system boundaries, allocation and impact categories. It is natural that scientists, consultants and companies have been looking for simplified models.

Main strategies in simplifying ISO-LCA can be discussed along the lines of the two major phases of LCA: inventory analysis and impact assessment.

In inventory analysis, simplifications include the following:

- replacing the time-consuming step of data collection by using readily available general purpose databases, such as ecoinvent, at least for a substantial part of the analysis, even when these datasets are not fully representative for the question under study;
- neglecting substantial parts of the product system, e.g., leaving out all capital goods;
- using IO-based LCA (or EIOA) instead of the ISO-recommended process-based LCA16;
- focusing on a selection of environmental flows only, e.g., only on inputs (like in MIPS), or only on greenhouse gases (ref).

In impact assessment, simplifications include the following:

- relying on readily available impact models and characterisation factors, even when these are not fully representative for the question under study;
- focusing on a small group of impact categories, e.g., only on climate change and acidification;
- using proxy indicators, such as total mass or cumulative energy.

There are many more ways of simplifying LCA.

[16] Some (e.g., Lave et al., 1995) argue that this is not a simplification, but rather a more complete form of doing LCA, and that process-based LCA (“SETAC LCA”) is only a crude approximation.

In fact, the boundary between full LCA and simplified LCA is not clear. Even highly sophisticated LCA studies use to some extent readily available data and leave out certain things. Moreover, the boundary between simplified LCA and another tool is not clear. Energy analysis, for instance, can be considered as a simplified form of LCA, focusing on flows of energy only. However, it was developed prior to LCA, not as a strategy to simplify LCA. It can only be considered post hoc as a simplification to LCA. Probably, energy analysts will take the opposite point of view, claiming that LCA is an extension to energy analysis.

LCA, on its turn, can be considered to be a simplification as well. ISO-LCA generally ignores spatial and temporal information, is based on linear modelling of technologies, and excludes many behavioural mechanisms. These are all simplifications. A question is then: of what is it a simplification? There is no generally recognized model that includes these features, and which can serve as a benchmark of ISO-LCA. In the end, every model is by definition a simplification of the real underlying phenomena.

4 Existing approaches and models classified in framework

An inventory of existing methods and models is provided in Appendix E. Based on criteria developed in this paper and in WP 3 a selection of these methods and models will be further analyzed in an S(trengths) W(eaknesses) O(pportunities) T(hreats) analysis. The methods and models inventoried will also be further analysed in WP 5. In both WP3 and WP5, also the practical aspects discussed in Chapter 5 will be included and further elaborated. In addition, a simple case study will be developed for demonstrating the practical application of some of these models. This case study aims to demonstrate how various models are typically used for giving insight on various aspects of a study. Thus the differences of the models can more easily be illustrated and compared in light of the SWOT analysis.

In this Chapter, we will give a few examples of how different methods/models fit in the general framework as developed in Chapter 3. For each of the following categories, we will give one example:

- ISO-LCA;
- other forms of LCA;
- other LC methods/models;
- macro- and meso-societal methods/models;
- combined methods/models;
- simplified methods/models.

In Appendix E the preliminary result is given for each of these categories of an inventory of approaches published in literature.

The discussion in the previous Chapter may be summarized in an analytical framework that can be used to categorize methods and models for sustainability analysis. A start is made below. The categorization of other methods and models to this scientific framework will take place as part of WP3 and WP5, and will be reported in the same format. Experiences gained while applying the framework in WP3 and WP5 may lead to adjustments of the framework, which will be taken into account in D15.

4.1 ISO-LCA

Name: ISO-LCA
Alternative names: life cycle assessment; life cycle analysis; LCA
Typology: cradle-to-grave analysis of a product or service
References to method: Anonymous (2006a); Anonymous (2006b); Lundie et al. (2006)
References to selected case studies: Gorrée et al. (2002); Ekvall & Andrae (2005); Scharnhorst et al. (2006)
Typology: cradle-to-grave analysis of a product or service

Aspect	**general**	**relationships**	**time**	**space**
population	fixed: functional unit		f.u. for a specified time	f.u. for a specified place
affluence				
technology	defined in terms of unit process data		related to time of f.u.	world-wide
economic chain	simple physical flows	linear, fixed coefficients	for a specified time	for a specified place
social aspects	not discussed in general			
institutional setting				
environment			aggregated over time	aggregated over places
environmental pressure	simple physical flows	linear, fixed coefficients		
environmental state	multi-media fate and exposure model	linear, fixed coefficients		
environmental impact				

References:

- Anonymous (2006a). Environmental management - Life cycle assessment - Principles and framework (ISO/FDIS 14040:2006(E)). ISO, Geneva.
- Anonymous (2006b). Environmental management - Life cycle assessment - Requirements and guidelines (ISO/FDIS 14044:2006). ISO, Geneva.
- Lundie, S., A. Ciroth & G. Huppes (2006). Inventory methods in LCA: methodology issues. Final Draft for Review. UNEP/SETAC.
- Gorrée, M., J. Guinée, G. Huppes & L. van Oers (2002). Environmental life cycle assessment of linoleum. Int. J.LCA 11:5,158-166.
- Ekvall T. & A. Andrae (2006). Attributional and consequential environmental assessment of the shift to lead-free solders. Int. J. LCA 11 (5): 344-353.
- Scharnhorst, W., H.-J. Althaus, L. M. Hilty & O. Jolliet (2006). Environmental assessment of end-of Life treatment options for a GSM 900 antenna rack. Int. J.LCA 11 (6): 425-436.

4.2 Other LC approaches

4.2.1 Material flow analysis

Name: material flow analysis
Alternative names: material flow accounting; MFA; substance flow analysis; SFA (is often considered as a specification of MFA)
Typology: investigation of flows and stocks of any material-based system, based on law of conservation of matter
References to method: Brunner & Rechberger (2004); EUROSTAT (2001)
References to selected case studies: PHARE (1997); Spatari et al. (2002); Moll et al. (2005)

Aspect	**general**	**relationships**	**time**	**space**
population	fixed spatial and temporal boundaries		specific time span, e.g. one year	specific region, e.g. a country or a city
affluence				
technology	not an explicit parameter of the model			
economic chain	simple physical flows and stocks aggregated or disaggregated for sectors	law of conservation of matter	for a specified time span	for a specified place
social aspects	not discussed in general			
institutional setting				
environment	bulk material indicators plus several evaluation methods connected to flows and stocks			
environmental pressure	resources, emissions, accumulations		for a specified time span	for a specified place
environmental state	in general not present			
environmental impact				

References:

- Brunner, Paul H. & Helmut Rechberger (2004). Practical Handbook of Material Flow Analysis, Advanced Methods in Resource and Waste Management. ISBN 1-5667-0604-1 Lewis Publishers.
- PHARE (1997). Nutrient Balances for Danube Countries, Final Report Project EU/AR/102A/91, Service Contract 95-0614.00, PHARE Environmental Program for the Danube River Basin ZZ 9111/0102. TU Vienna / TU Budapest, Austria.
- Spatari, S., M. Bertram, K. Fuse, T.E. Graedel & H. Rechberger (2002). The contemporary European copper cycle: 1 year stocks and flows. Ecological Economics 42: 27–42.
- Moll S., S.Bringezu & H. Schütz (2005). Resource use in European Countries. Wuppertal Report ISSN 1862-1953.
- EUROSTAT (2001). Economy-wide material flow accounts and derived indicators. A methodological guide. European Communities, Brussels.

4.3 Macro- and meso-societal models

4.3.1 General Equilibrium Model for studying Economy – Energy - Environment Interactions

Name: General Equilibrium Model for studying Economy – Energy - Environment Interactions
Alternative names: GEM – E3
Typology: combined model with a trade-off among economy, environment and social aspects, internalisation of environment and social/institutional aspects in economic terms, limited indicators for environment and social aspects
References to method: http://www.gem-e3.net/themodel.htm; http://gem-e3.zew.de/
References to selected case studies: Bahn (2001); http://ec.europa.eu/environment/climat/studies.htm; http://www.gem-e3.net/

Aspect	**general**	**relationships**	**time**	**space**
population	recursive data for regions, countries, and world		recursive on years	aggregated over country, EU, world
affluence	softly covered and related to the market mechanism			
technology	related to exogenous and endogenous factors			
economic chain	General Equilibrium Model based on I/O tables	non linear		
social aspects	softly covered and related to the market mechanism			
institutional setting	includes: taxes, permits and technical standards; related to the market mechanisms			
environment	specific module to represent the effect of different environmental policies on the EU economy and environment state on a marginal basis			
environmental pressure	emissions (SO_2, NOX, VOC, PM, CO_2), transformation and transport to calculate change in concentration levels of primary and secondary pollutants; physical units	non linear functions related to: exogenous emission factor, additional policy constraints, substitution of energy sources, abatement rate, share of energy demand by sectors		
environmental state	physical units of concentration/deposition	linear, fixed coefficients		
environmental impact	public health, territorial ecosystems and materials, global warming	linear, fixed coefficients (based on ExternE)		

References:

- Boringer, C. & A. Loschel (2006). Computable general equilibrium models for sustainability impact assessment. Status quo and prospects. Ecological Economics 60: 49-64.
- Otto, V., A. Loschel & R. Dellink (2005). Energy biased technical change - a CGE analysis. Fondazione ENI Enrico Mattei (FEEM) - Nota di lavoro 90, Milano.
- Loschel, A.(2004). Technological change in economic models of environmental policy, a survey. Ecological Economics 43: 105-126.
- Rasmussen, T. N. & T.F. Rutherford (2004). Modelling overlapping generations in a complementary format. Journal of Economics Dynamics and Control 28 (7): 1383-1409.
- Bahn, O. (2001). Combining policy instruments to curb greenhouse gas emissions. European Environment 11(3): 163-171.

4.4 Combined models

4.4.1 Integrated hybrid LCA

Name: Integrated hybrid LCA (not included: tiered hybrid analysis; IO based hybrid analysis)
Alternative names:
Typology: integration in a common matrix framework of functional flow based (foreground) system with a commodity based (background) system
References to method: Suh (2004); Suh et al. (2004); Suh & Huppes (2005)
References to selected case studies: no peer-reviewed papers have been found

Aspect	general	relationships	time	space
population	fixed: functional unit		f.u. for a specified time	f.u. for a specified place
affluence				
technology	the background system is described in terms of I/O table representing the present existing technology			
economic chain	physical and monetary flows	linear and fixed coefficient	for a specified time span	for a specified place (country)
social aspects	no			
institutional setting	no			
environment	several evaluation methods connected to physical flows			
environmental pressure	simple physical flows	linear, fixed coefficients	aggregated over time	aggregated over places
environmental state	not elaborated; however the ISO-LCA impact assessment can be applied here			
environmental impact				

References:

- Suh, S. (2004). Functions, commodities and environmental impacts in an ecological-economic model. Ecological Economics 48: 451-467.
- Suh, S., M.Lenzen, G.J.Treloar, H.Hondo, A.Horvath, G.Huppes, O.Jolliet, U.Klann, W.Krewitt, Y.Moriguchi, J.Munksgaard & G.Norris (2004). System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches. Environmental Science and Technology 38 (3): 657-664.
- Suh, S. & G. Huppes (2005). Methods for Life Cycle Inventory of a product. Journal of Cleaner Production 13: 687-697.

4.5 Simplified models

4.5.1 Streamlined life-cycle assessment

Name: streamlined life-cycle assessment
Alternative names: SLCA; Design for Environment; DfE; matrix approach; AT&T abridged life-cycle assessment
Typology: Qualitative or semi-quantitative relative assessment matrix (life cycle stages - environmental stressors)
References to method: Graedel (1998); Graedel et al. (1995); Masoni et al. (2004)
References to selected case studies: Graedel (1998); Masoni et al. (2004)

Aspect	**general**	**relationships**	**time**	**space**
population	fixed: functional unit		f.u. for a specified time	f.u. for a specified place
affluence				
technology	input data depending on specific technology			
economic chain	product life cycle stages		for a specified time span	for a specified place
social aspects	no			
institutional setting	no			
environment	evaluation methods based on relative rating using appropriate checklists			
environmental pressure	based on readily available methods and factors		aggregated over time	aggregated over places
environmental state				
environmental impact		linear and fixed coefficient		

References:

- Graedel, T.E. (1998). Streamlined Life-Cycle Assessment. Prentice Hall.
- Graedel T.E., B.R. Allenby & P. Comrie (1995). Matrix approaches to abridged life cycle assessment, Environmental Science and Technology 29: 134A-139A.
- Chen, J.L. & Wai-Kit Chow (2003). Matrix-Type and Pattern-Based Simple LCA for Eco-Innovative Design of Products. 3rd International Symposium on Environmentally Conscious Design and Inverse Manufacturing, 2003. EcoDesign '03.
- Masoni, P., B. Sára, E. Scimia & A. Raggi (2004). VerdEE: a tool for adoption of life cycle assessment in small and medium sized enterprises in Italy. Progress in Industrial Ecology 1 (1/2/3): 203-228.

5 Some practical issues

The scientific framework of Chapter 3 is meant to categorize existing tools for sustainability analysis in a systematic way. Moreover, it provides a more scientific foundation. This chapter explores some of the more practical aspects. All the models require data, and some of the data may be common to several models. The hard linking of models (see Section 3.5) can be accomplished by uniting several models within one software tool.

5.1 Data

The tools discussed above have certain features in common. For instance, many of them deal with environmental information in terms of emissions of pollutants. It is a natural question to ask if convenient data sharing and joint databases are available or may be constructed.

To some extent, this is the case. But broadening and deepening imply in any case an increase of the data requirements. Addressing more impact categories means knowing more characterisation factors and probably more interventions. Including more mechanisms means needing elasticities and other variables presently not part of LCA databases. Extending sustainability to the social domain means collecting social data at the level of unit processes. In designing broader and deeper models, the “life cycle effort” of creating the model and getting the data should be kept in mind.

5.2 Format

The data sharing discussed in the previous section may be helpful to circumvent the collection of identical data at different places. However, even when data is available at public place, the issue of data format can create problems in using these data. Retyping thousands of number from a monitor into a program is not a very economic thing. One would like to be able to reuse data in an automated way. For instance, a computer program for hybrid LCA would ideally be able to import EIOA-databases, directly obtained from statistical agencies.

This creates at present quite some problems. We mention the following:

- file formats differ across programs and databases;
- nomenclature of industrial sectors, products, pollutants, etc. differ across tools and countries;
- units are different between programs and databases, and are even sometimes not specified;
- economic information is often specified in monetary units, and these do not only differ per country, but also per year. A Euro in Germany in 2002 is different from a Euro in Slovenia in 2007.

There are solutions, some of which are emerging:

- New information technologies (like xml and rss) may provide simpler data exchange.
- Standards for data formats have been published in several areas. Unfortunately, for LCA there are several competing standards: ISO 14048, EcoSpold, Spine and ELCD.

- National and international initiatives for harmonized and well-structured databases are increasing. For LCA, we mention here the Swiss ecoinvent consortium and the European Reference Life Cycle Data System.
- Standardized nomenclature is available for, e.g. chemicals (the CAS-numbers) and industrial sectors (the NACE classification), although these are not always sufficiently detailed, and other countries or areas of research sometimes apply competing standards (like the BEA classification).

In the creation of new standards for formats, databases and nomenclatures, we recommend to be open for a broad view, and to create an open standard that may be changed.

5.3 Software

There is a large choice of software for LCA at present (Siegenthaler, 2005). Some of these programs are general purpose programs, but the integration of dedicated databases implies that many of them have niche market, e.g. the building sector, energy systems, or waste treatment facilities. Some of the tools support the calculation of more than merely environmental information, e.g. a life cycle cost or eco-efficiency. But most of the tools are restricted to an environmental analysis on the basis of a functional unit, using the assumption of a linear steady-state model. Broadening LCA to the social domain and deepening LCA to include time-specific or non-linear features is not possible for these models. The development of (new) LCA will require the redesign of data interfaces, computational algorithms, and output screens.

References

1. Adkins, C.J. (1983). Equilibrium thermodynamics. Third edition. Cambridge University Press, Cambridge.
2. Andersson P., M. Simonson, C. Tullin, H. Stripple, J.-O. Sundqvist & T. Paloposki (2004). "Fire-LCA Guidelines", Nordtest Technical Report TR 583, ISSN 0283-7234.
3. Anonymous (1974). Energy analysis workshop on methodology and conventions. IFIAS, Stockholm.
4. Anonymous (2006a). Environmental management - Life cycle assessment – Principles and framework (ISO/FDIS 14040:2006(E)). ISO, Geneva.
5. Anonymous (2006b). Environmental management - Life cycle assessment – Requirements and guidelines (ISO/FDIS 14044:2006). ISO, Geneva.
6. Ansems, A., S. van Leeuwen, J. Guinée & P. Frankl (2005). Making Life-Cycle Information and Interpretative Tools Available. TNO-Report, B&O-A R2005/326, Apeldoorn, the Netherlands.
7. Assies, J.A. (1998). A risk-based approach to life-cycle impact assessment. Journal of Hazardous Materials 61, 23–29.
8. A-Test (2005). Sustainability A-Test, website: http://ivm5.ivm.vu.nl/sat/
9. Ayres, R.U. & A.V. Kneese (1969). Production, consumption, and externalities. The American Economic Review LIX, 282-297.
10. Ayres, R.U. (1989). Industrial metabolism. Technology and Environment. In: Ausubel, J.H. & H.E. Sladovich. National Academy Press, Washington.
11. Azapagic, A. & R. Clift (1999). Allocation of environmental burdens in multiple-function systems. J Cleaner Prod 7(2):101-119.
12. Azapagić, A. & R. Clift (1999). Allocation of environmental burdens in multiple-function systems. Journal of Cleaner Production 7, 101-119.
13. Azapagic, A. (1996). Environmental System Analysis: the Application of Linear Programming to Life Cycle Assessment - Volume 1. Ph.D. Thesis. Guilford, UK: University of Surrey.
14. Balteiro, L.-D. & C. Romero (2004). In search of a natural systems sustainability index. Ecological Economics 49, 401-405.
15. Barbier, E., A. Markandya & D.W. Pearce (1990). Environmental sustainability and cost - benefit analysis. Environment and Planning A, 22 (9):1259-1266.
16. Bare J.C., G.A. Norris, D.W. Pennington & T. McKone (2002). TRACI - The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts. Journal of Industrial Ecology 6:3-4, 49-78.
17. Basset-Mens, C.; Anibar, L.; Durand, P.; Werf, H.M.G. van der. Spatialised fate factors for nitrate in catchments: modelling approach and implication for LCA results. Science of the Total Environment 367 (2006), 376-382.
18. Baumgärtner, S. & J. de Swaan Arons (2003). Necessity and inefficiency in the generation of waste. A thermodynamic analysis. Journal of Industrial Ecology 7:2, 113-123.
19. Bellekom, S., J. Potting & R. Benders (2006). Feasibility of Applying Site-dependent Impact Assessment of Acidification in LCA. Int. J. LCA 11 (6), 417-424.

20. Bertalanffy, L. von (1968). General system theory. Foundations, development, applications. Revised edition. George Braziller, New York.
21. Björk, H. & A. Rasmuson (2002). A method for life cycle assessment environmental optimisation of a dynamic process exemplified by an analysis of an energy system with a superheated steam dryer integrated in a local district heat and power plant. Chem. eng. j., vol. 87, no3, pp. 381-394.
22. Chertow, M.R. (2000). The IPAT equation and its variants. Changing views of technology and environmental impact. Journal of Industrial Ecology 4:4, 13-29.
23. Claeson, U. (2000). Analyzing Technological Change Using Experience Curves – A Study of the Combined Cycle Gas Turbine Technology. LicEng thesis, Chalmers University of Technology, Gothenburg, Sweden.
24. Curran, M.A., M. Mann & G. Norris (2001). Report on the International Workshop on Electricity Data for Life Cycle Inventories, Cincinnati, EPA 600/R-92/041, USA: US Environmental Protection Agency.
25. Cyert R.M. & J.G. March (1963). A behavioural theory of the firm. Prentice-Hall, Englewood Cliffs, NJ.
26. EC (2002). The World Summit on Sustainable Development - People, planet, prosperity. Office for Official Publications of the European Communities, http://ec.europa.eu/environment/wssd/documents/wssd_brochure.
27. Ehrlich, P.R. & J.P. Holdren (1971). Impact of population growth. Science 171, 1212-1217.
28. Ekvall T, A.-M. Tillman & S. Molander (2005). Normative ethics and methodology for life cycle assessment. J. Cleaner Prod. 13(13-14):1225-1234.
29. Ekvall, T. & B.P. Weidema (2004). System Boundaries and Input Data in Consequential Life Cycle Inventory Analysis. Int J LCA 9(3):161-171.
30. Ekvall, T. (1999). System Expansion and Allocation in Life Cycle Assessment. Ph.D. Thesis. Gothenburg, Sweden: Chalmers University of Technology.
31. Ekvall, T. (2000). A market-based approach to allocation at open-loop recycling. Resources, Conservation and Recycling 29(1-2):93-111.
32. Ekvall, T. (2003). Tools for consequential modelling. Poster presented at 13th SETAC-Europe Annual Meeting in Hamburg, April 2003.
33. Ekvall, T., N. Mattsson & M. Münter (2005). System-wide environmental consequences of Vistar combustion in Stenungsund – Feasibility study. Report 2005:1. Gothenburg, Sweden: Division of Energy Technology, Chalmers University of Technology.
34. Ernst & Young (2000). Developing the Foundation for Integrated Product Policy in the EU. DG Environment, European Commission, Brussels.
35. Eshet, T, O. Ayalon & M. Shechter (2006). An inclusive comparative review of valuation methods for assessing environmental goods and externalities. International Journal of Business Environment, Volume 1, Number 2: 190-210.
36. Friedman, M. (1976). Price theory. Aldine, Chicago, USA.
37. Frischknecht, R. (1998). Life cycle inventory analysis for decision-making. Scope-dependent inventory system models and context-specific joint product allocation. PhD-thesis Swiss Federal Institute of Technology Zurich, Zurich.
38. Georgescu-Roegen, N. (1971). The entropy law and the economic process. Harvard University Press, Cambridge.

39. Graedel, T.E. & B.R. Allenby (2003). Industrial ecology. Second edition. Pearson Education, Inc., Upper Saddle River.
40. Gramberger, M. (2001). Handbook on information, consultation and public participation in policy making. OECD Development Centre, Paris.
41. Grießhammer, R., C. Benoît, L.C. Dreyer, A. Flysjö, A. Manhart, B. Mazijn, A.-L. Méthot & B.P. Weidema (2006). Feasibility Study: Integration of social aspects into LCA. UNEP-SETAC Life Cycle Initiative, website: lcinitiative.unep.fr/includes/file.asp?site=lcinit&file=2FF2C3C7-536F-45F2-90B4-7D9B0FA04CC8.
42. Guinée, J.B. (Ed.), M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. de Koning, L. van Oers, A. Wegener Sleeswijk, S.Suh, H.A. Udo de Haes, J.A. de Bruijn, R. van Duin and M.A.J. Huijbregts (2002). Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Series: Eco-efficiency in industry and science. Kluwer Academic Publishers. Dordrecht.
43. Guinée, J.B., R. Heijungs & G. Huppes (2004). Economic Allocation: Examples and Derived Decision Tree. Int. J. LCA **9** (1), 23-33.
44. Hauschild, M. & H. Wenzel (1998). Environmental assessment of products. Volume 2: Scientific background. Chapman & Hall, London.
45. Hauschild, M.Z., J. Potting, O. Hertel, W. Schöpp & A. Bastrup-Birk (2006). Spatial Differentiation in the Characterisation of Photochemical Ozone Formation: The EDIP2003 Methodology. International Journal of Life Cycle Assessment 11 Special Issue 1, 72-80.
46. Heijungs, R. & S. Suh (2002). The computational structure of life cycle assessment. Kluwer Academic Publishers, Dordrecht.
47. Heijungs, R. (1997). Economic drama and the environmental stage. Formal derivation of algorithmic tools for environmental analysis and decision-support from a unified epistemological principle. PhD-thesis Leiden University, Leiden.
48. Hellweg, S., T. Hofstetter & K. Hungerbühler (2003). Discounting and the Environment - Should Current Impacts be Weighted Differently than Impacts Harming Future Generations? International Journal of Life Cycle Assessment 8:1, 8-18.
49. Hertwich, E.G., J.K. Hammitt & W.S. Pease (2000). A theoretical foundation for life-cycle assessment: recognizing the role of values in environmental decision making. Journal of Industrial Ecology 4:1, 13-28.
50. Hirao, M. (1999). Dynamic LCA for Technology Assessment. Paper presented at the AIST Symposium on Development of New Methodologies for LCA - Social LCA and Dynamic LCA - March 3, 1999 in Tsukuba, Japan.
51. Hobbs, B.F. & P. Meier (2000). Energy decisions and the environment: a guide to the use of multicriteria methods. Kluwer Academic Publishers, Boston/Dordrecht/London.
52. Hofstetter, P. (1998). Perspectives in life cycle impact assessment. Kluwer Academic Publishers, Boston.
53. Huijbregts M.A.J., W. Schöpp, E. Verkuijlen, R. Heijungs & L. Reijnders (2000). Spatially Explicit Characterization of Acidifying and Eutrophying Air Pollution in Life-Cycle Assessment. Journal of Industrial Ecology 4:3, 75-92.
54. Huppes, G. & M. Ishikawa (2005). A framework for quantified eco-efficiency analysis. Journal of Industrial Ecology 9(4): 25-41.

55. Huppes, G. (1993). Macro-environmental policy: principles and design. Elsevier, Amsterdam.
56. Huppes, G., M.D. Davidson, J. Kuyper, L. van Oers, H.A. Udo de Haes & G. Warringa (2006). Eco-efficient environmental policy in oil and gas production in The Netherlands. Ecological Economics. doi:10.1016/j.ecolecon.2006.06.011.
57. Ibenholt, K. (2002). Materials flow analysis and economic modelling, In: Ayres RU, Ayres LW, editors. Handbook of Industrial Ecology. Cheltenham: Edward Elgar, 177-184.
58. Jolliet, O., R. Müller-Wenk, J. Bare, A. Brent, M. Goedkoop, R. Heijungs, N. Itsubo, C. Peña, D.W. Pennington, J. Potting, G. Rebitzer, M. Stewart, H.A. Udo de Haes & B.P. Weidema (2003). The LCIA midpoint-damage framework of the UNEP/SETAC Life Cycle Initiative. International Journal of Life Cycle Assessment 9:6, 394-404.
59. Karlsson, R. (1998). Life Cycle Considerations in Sustainable Business Development. Ph.D. Thesis. Gothenburg, Sweden: Chalmers University of Technology.
60. Kendall, A. (2004). A Dynamic Life Cycle Assessment Tool for Comparing Bridge Deck Designs. Center for Sustainable Systems – University of Michigan.
61. Krewitt, W., P. Mayerhofer, A. Trukenmüller & R. Friedrich (1998). Application of the Impact Pathway Analysis in the Context of LCA. The Long Way from Burden to Impact. International Journal of Life Cycle Assessment 3:2, 86-94.
62. Krewitt, W., T. Heck, A. Trukenmüller & R. Friedrich (1999). Environmental damage costs from fossil electricity generation in Germany and Europe. Energy Policy 27, 173-183.
63. Lave, L.B., E. Cobas-Flores, C.T. Hendrickson & F.C. McMichael, (1995). Using input-output analysis to estimate economy-wide discharges. Environmental Science & Technology 29:9, A420-426.
64. Martinez-Alier, J., G. Munda & J. O'Neill (1998). Weak comparability of values as a foundation for ecological economics. Ecological Economics 26: 277-286.
65. Masini, A. & P. Frankl (1997). A dynamic life-cycle analysis of photovoltaic industry: future scenarios and technological innovations for large scale diffusion of solar energy systems. Innovation in Technology Management - The Key to Global Leadership. PICMET '97: Portland International Conference on Management and Technology.
66. Mattsson, N. (1997). Internalizing technological development in energy systems models. LicEng thesis, Chalmers University of Technology, Gothenburg, Sweden.
67. Mattsson, N., T. Unger & T. Ekvall (2003). Effects of perturbations in a dynamic system - The case of Nordic power production. In Unger T. Common energy and climate strategies for the Nordic countries - A model analysis. PhD thesis, Department of Energy Technology, Chalmers University of Technology, Göteborg, Sweden.
68. Moriguchi, Y. & A. Terazono (2000). A Simplified Model for Spatially Differentiated Impact Assessment of Air Emissions. Int. J. LCA.5 (5), 281-286.
69. Moriguchi, Y. & A. Terazono (2000). A Simplified Model for Spatially Differentiated Impact Assessment of Air Emissions. International Journal of Life Cycle Assessment 5:5, 281-286.
70. Nigge, K.-M. (2001a). Generic Spatial Classes for Human Health Impacts, Part I: Methodology. Int. J. LCA 6 (5), 257-264.

71. Nigge, K.-M. (2001b). Generic Spatial Classes for Human Health Impacts, Part II. Application in a Life Cycle Assessment of Natural Gas Vehicles. Int . J. LCA 6 (6), 334-338.
72. Norris, G.A. (2006). Social Impacts in Product Life Cycles - Towards Life Cycle Attribute Assessment. International Journal of Life Cycle Assessment 11 Special Issue 1, 97-104
73. Oka, T., M. Ishikawa, Y. Fujii & G. Huppes (2005). Calculating cost-effectiveness for activities with multiple environmental effects using the maximum abatement cost method. Journal of Industrial Ecology 9(4): 97-103.
74. Oreskes, N., K. Shrader-Frechette & K. Belitz (1994). Verification, validation, and confirmation of numerical models in the earth sciences. Science 263 (1994), 641-645.
75. Pauli, G. (1997). Zero emissions: the ultimate goal of cleaner production. Journal of Cleaner Production 5:1/2, 109-113.
76. Pehnt, M. (2006). Dynamic life cycle assessment (LCA) of renewable energy technologies. Renew. energy, 31:1, 55-71.
77. Pennington, D.W., M. Margni, C. Ammann & O. Jolliet (2005). Multimedia fate and human intake modelling: spatial versus nonspatial insights for chemical emissions in Western Europe. Environmental Science & Technology 39, 1119-1128.
78. Potting J., W. Schõpp, K. Blok & M. Hauschild (1998). Site-dependent life-cycle assessment of acidification. Journal of Industrial Ecology 2:2, 63-87.
79. Potting, J. & M. Hauschild (1997). Predicted Environmental Impact and Expected Occurrence of Actual Environmental Impact. Part II: Spatial Differentiation in Life-Cycle Assessment via the Site-Dependent Characterisation of Environmental Impact from Emissions. International Journal of Life Cycle Assessment 2:4, 209-216.
80. Potting, J. & M. Hauschild (1997). Predicted Environmental Impact and Expected Occurrence of Actual Environmental Impact. Part I: The Linear Nature of Environmental Impact from Emissions in Life-Cycle Assessment. International Journal of Life Cycle Assessment 2:3 (1997), 171-177
81. Potting, J. (2000). Spatial differentiation in life cycle impact assessment. A framework, and site-dependent factors to assess acidification and human exposure. PhD-thesis Universiteit Utrecht.
82. Rabl, A., A. Markandya, A. Hunt, P. Bickel & R. Friedrich (2004). ExternE-Pol. Externalities of Energy: Extension of accounting framework and Policy Applications. Final Report contract N° ENG1-CT2002-00609. EC DG Research.
83. Rubik, R. & D. Scheer (2007). Integrated product policy and governance – concepts and European approaches. Paper submitted to J Cleaner Prod.
84. Sandén, B. & M. Karlström (2007). Positive and negative feedback in consequential life-cycle assessment. J Cleaner Prod (in press).
85. Schneider, F. (1996). Analyse des Reemplois, Recyclages, Valorisations de Dechets par l'Etude de Systems Cascade. Ph.D. Thesis. Lyon, France: l'Institut National des Sciences Appliquees de Lyon (in French).
86. Siegenthaler, C.P., A. Braunschweig, G. Oetterli & S. Furter (2005). LCA software guide 2005. Market overview - Software portraits. ÖBU, Zürich.
87. Smeets, E. & R. Weterings (1999). Environmental indicators. Typology and overview. European Environmental Agency, Copenhagen.

88. Sumaila, U.R. & C. Walters (2005). Intergenerational discounting: a new intuitive approach. Ecological Economics 52, 135-142
89. Thompson, G. (1991). Introduction to Networks. In: Thompson, G., J. Frances, R. Levacic & J. Mitchell (eds.). Markets, Hierarchies and Networks: the Co-ordination of Social Life. London: Sage.
90. Tillman, A.-M. (2000). Significance of decision-making for LCA methodology. Environ. Impact Assess. Rev. 20:113-123.
91. Tolle, D.A. (1997). Regional Scaling and Normalization in LCIA - Development and Application of Methods. Int. J. LCA 2 (4), 197-208.
92. Trinius, W. (1999). Environmental Assessment in Building and Construction. Ph.D. Thesis. Stockholm, Sweden: Royal University of Technology.
93. Tukker A., R. Kleijn, L. van Oers & E. Smeets (1997). Combining SFA and LCA: The Swedish PVC Analysis. Journal of Industrial Ecology 1:4, 93-116
94. Udo de Haes, H.A., R. Heijungs, G. Huppes & S. Suh (2004). Three strategies to overcome the limitations of life-cycle assessment. Journal of Industrial Ecology 8:3 (2004), 19-32.
95. Wegener Sleeswijk, A. (2003). General prevention and risk minimization in LCA. A combined approach. Environmental Science & Pollution Research 10:1, 69-77.
96. Weidema B. (2000). Avoiding Co-Product Allocation in Life-Cycle Assessment. Journal of Industrial Ecology 4:3, 11-33.
97. Weidema, B.P. (1993). Market aspects in product life cycle inventory methodology. J Cleaner Prod 1(3-4):161-166.
98. Weidema, B.P. (2003). Market information in life cycle assessment. Environmental Project no. 863. Danish Environmental Protection Agency, Copenhagen.
99. Weidema, B.P., N. Frees & A.M. Nielsen (1999). Marginal production technologies for life cycle inventories. Int. J. LCA 4(1):48-56.
100. Wene, C.-O. (1996). Energy-Economy Analysis: Linking the Macroeconomic and Systems Engineering Approaches. Energy 21(9):809-824.
101. Werner, F. & R. Scholz (2002). Ambiguities in Decision-Oriented Life Cycle Inventories: The Role of Mental Models. International Journal of Life Cycle Assessment 7:6, 330-338.
102. Wiedmann, T., J. Minx, J. Barrett, R. Vanner & P. Ekins (2006). Sustainable Consumption and Production - Development of an Evidence Base: Resource Flows. Project commissioned by DEFRA. London: PSI and York: SEI.
103. Wright, T.P. (1936). Factors affecting the costs of airplanes. J Aeronautical Sciences 3:122-128. Referred to in Claeson U. (2000) Analyzing Technological Change Using Experience Curves – A Study of the Combined Cycle Gas Turbine Technology. LicEng thesis, Chalmers University of Technology, Gothenburg, Sweden.
104. Wrisberg, N., H.A. Udo de Haes, U. Triebswetter, P. Eder & R. Clift (2002). Analytical tools for environmental design and management in a systems perspective. Kluwer Academic Publishers, Dordrecht

Appendix A: Terms & abbreviations

Terms

economic mechanism
causal relationship that connects the level of two economic activities

evaluation
set of approaches to rank alternatives on different criteria (quantitative and/or qualitative)

life cycle approaches [for sustainability analysis and decision support]
all concepts, methods, models and tools which incorporate supply and demand chains and include at least one environmental aspect of sustainability.

life cycle concepts
general, non-quantified approaches for viewing sustainability and indicating strategic directions for sustainable development.

life cycle methods and models
all quantified empirical and normative analysis for sustainability decision support.

life cycle tools
all software and data bases used for application of life cycle methods and models.

life cycle assessment (ISO-LCA)
compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle; the term may refer to either a procedural method or a specific study

life cycle analysis (new LCA)
LCA as a result of innovation, in contrast to ISO-LCA

valuation
determination of economic value of a non-market item or external effect; often used as a sub-option of weighting, meaning weighting in monetary units

weighting
within ISO-LCA: a step of Impact assessment in which the (normalised) indicator results for each impact category assessed are assigned numerical factors according to their relative importance, multiplied by these factors and possibly aggregated; weighting is based on value-choices (e.g. monetary values, standards, expert panel)
broader (e.g. new-LCA): one formalized approach to evaluation in which the different quantified criteria (environmental, social, economic) assigned numerical factors according to their relative importance, multiplied by these factors and possibly aggregated

Abbreviations

3R	Reduce, Re-use, Recycle
CALCAS	Co-ordination Action for innovation in Life-Cycle Analysis for Sustainability
CBA	Cost-Benefit Analysis
CGE	Computable General Equilibrium
CLCA	Consequential Life Cycle Assessment
CMLCA	Chain Management by Life Cycle Assessment
DOW	Description of Work

DPSIR	Drivers, Pressures, State, Impact, Responses
E3ME	Energy-Environment-Economy Model for Europe
EC	European Commission
EE	Eco-Efficiency
EIOA	Environmentally extended Input-Output Analysis
EnvCGE	Environmentally extended Computable General Equilibrium
EU	European Union
GABI	Ganzheitliche Bilanzierung
GDP	Gross Domestic Product
GEM-E3	General Equilibrium Model for Energy-Economy-Environment
GWP	Global Warming Potential
IFIAS	International Federation of Institutes for Advanced Study
IO	Input-Output
IPAT	Impact, Population, Affluence and Technology
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
ISO-LCA	LCA according to the ISO 14040 Standards
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCIA	Life Cycle Impact Assessment
LCM	Life Cycle Management
LCTA	Life Cycle Technology Analysis
MATTER	Materials Technologies for greenhouse gas Emission Reduction
MCA	Multi-Criteria Analysis
MFA	Material Flow Accounting
MIPS	Material Input Per unit of Service
NAMEA	National Accounting Matrix including Environmental Accounts
new-LCA	LCA as a result of innovation, in contrast to ISO-LCA
NGO	Non-Governmental Organisation
PIOT	Physical Input-Output Table
PLA	ProduktLinienAnalyse
R&D	Research & Development
REAP	Resource and Energy Analysis Program
REEIO	Regional Environment-Economy Input-Output
SAM	Social Accounting Matrix
SETAC	Society for Environmental Toxicology and Chemistry
SETAC-LCA	LCA according to SETAC "Code of Practice" or SETAC working groups
SFA	Substance Flow Analysis
SWOT	Strengths, Weaknesses, Opportunities, Threats
UK	United Kingdom
UNEP	United Nations Environment Programme
UNEP-SETAC	United Nations Environment Programme - Society for Environmental Toxicology and Chemistry
WBCSD	World Business Council on Sustainable Development
WP	Work Package

Appendix B: Main structure of Sustainability A-Test

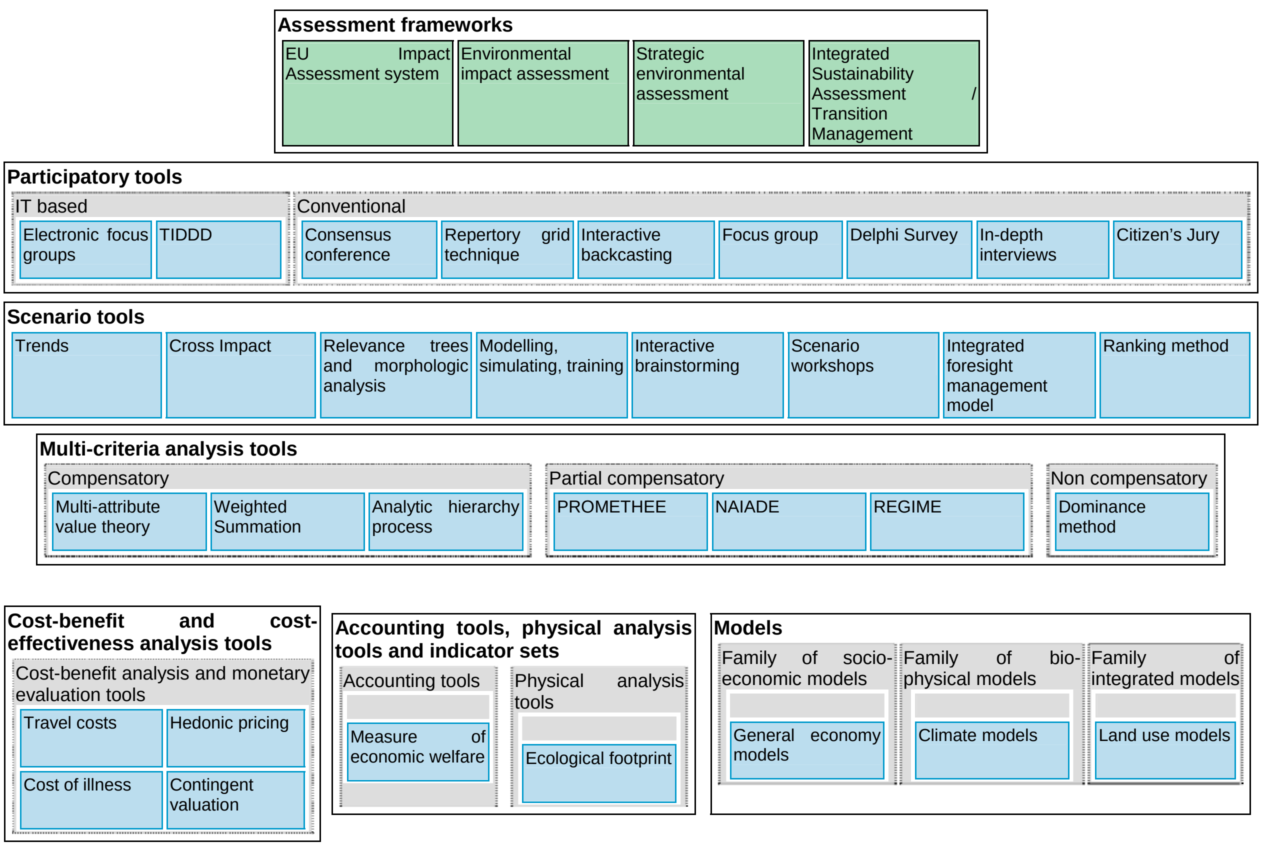
(Source: http://ivm5.ivm.vu.nl/sat/)

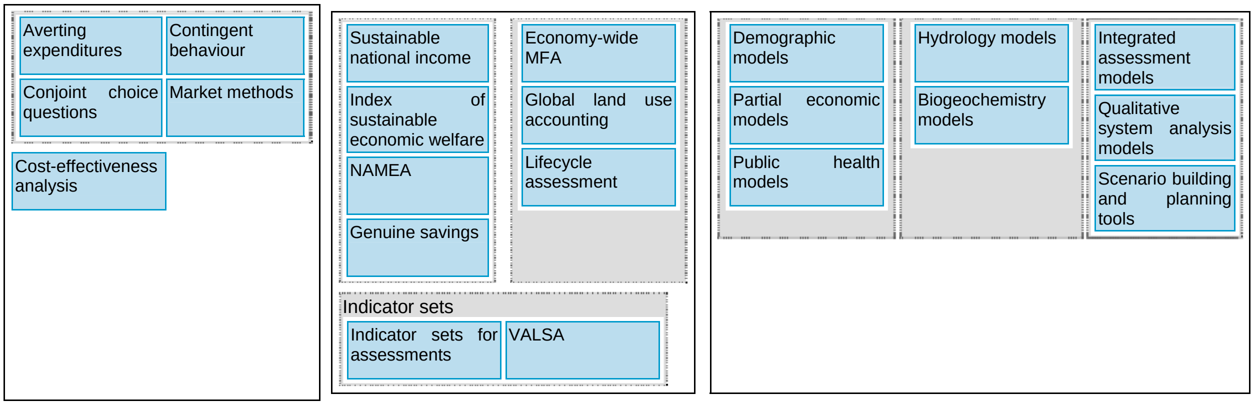
MAIN STRUCTURE
Assessment frameworks
Participatory tools
Scenario tools
Multi-criteria analysis tools
Cost-benefit and cost-effectiveness analysis tools
Accounting tools, physical analysis tools and indicator sets
Models

MAIN STRUCTURE	APPROACHES COVERED
Assessment frameworks	▪ EU Impact Assessment system ▪ Environmental impact assessment ▪ Strategic environmental assessment ▪ Integrated Sustainability Assessment / Transition Management
Participatory tools	▪ IT based o Electronic focus groups o TIDDD ▪ Conventional o Consensus conference o Repertory grid technique o Interactive backcasting o Focus group o Delphi Survey o In-depth interviews o Citizen's Jury
Scenario tools	▪ Trends ▪ Cross Impact ▪ Relevance trees and morphologic analysis ▪ Modelling, simulating, training Interactive brainstorming ▪ Scenario ▪ Integrated foresight management model workshops ▪ Ranking method
Multi-criteria analysis tools	▪ Compensatory o Multi-attribute value theory o Weighted Summation o Analytic hierarchy process ▪ Partial compensatory o PROMETHEE o NAIADE o REGIME ▪ Non compensatory o Dominance method
Cost-benefit and cost-effectiveness analysis tools	▪ Cost-benefit analysis and monetary evaluation tools o Travel costs o Cost of illness o Averting expenditures o Conjoint choice questions o Hedonic pricing o Contingent valuation o Contingent behaviour o Market methods ▪ Cost-effectiveness analysis o Cost-effectiveness analysis

Accounting tools, physical analysis tools and indicator sets	▪ **Accounting tools** o **Measure of economic welfare** o **Sustainable national income** o **Index of sustainable economic welfare** o **NAMEA** o **Genuine savings** ▪ **Physical analysis tools** o **Ecological footprint** o **Economy-wide MFA** o **Global land use accounting** o **Lifecycle assessment** ▪ **Indicator sets** o **Indicator sets for assessments** o **VALSA**
Models	▪ **Family of socio-economic models** o **General economy models** o **Demographic models** o **Partial economic models** o **Public health models** ▪ **Family of bio-physical models** o **Climate models** o **Hydrology models** o **Biogeochemistry models** ▪ **Family of integrated models** o **Land use models Integrated assessment models** o **Qualitative system analysis models** o **Scenario building and planning tools**

Sustainability A-Test Advanced Tools for Sustainability Assessment:




Averting expenditures
Contingent behaviour
Conjoint choice questions
Market methods
Cost-effectiveness analysis
Sustainable national income
Index of sustainable economic welfare
NAMEA
Genuine savings
Economy-wide MFA
Global land use accounting
Lifecycle assessment
Indicator sets
Indicator sets for assessments
VALSA
Demographic models
Partial economic models
Public health models
Hydrology models
Biogeochemistry models
Integrated assessment models
Qualitative system analysis models
Scenario building and planning tools

Appendix C: An Overview Presentation of the Fire-LCA concept

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Introduction and background

Environmental issues are a vital part of our society and the ability to perform accurate estimates and evaluations of environmental parameters is a vital tool in any work to improve the environment. In the 1980's the Life Cycle Assessment (LCA) methodology was developed in order to handle the system perspectives of different products and processes. However, the Life Cycle Assessment methodology also needs continuous improvements to incorporate new aspects and processes. An LCA typically describes a process during normal operation and abnormal conditions such as accidents are left out of the analysis, usually due to lack of a consistent methodology or relevant data. For example, LCA data for power production usually assume normal conditions without any accidents. Provisions for certain accidents in the analysis of the life-cycle could be included provided these could be specified in sufficient detail and occurred with sufficient regularity to make their inclusion relevant.

In traditional LCA models a higher fire performance is only included as a change in energy and material consumption and no account is taken of the positive effect of higher fire performance in the form of fewer and smaller fires. The emissions from fires contribute to the environmental impact from products and should be included in a more complete evaluation of the environmental impact of a product where the fire performance is an important parameter such as in electric and electronic products, furniture, electric cables etc. In cases where the fire performance is not a critical product performance characteristic (e.g. underground piping) one should not include this in the product LCA.

A methodology for the incorporation of fires into a Life Cycle Assessment has been developed by IVL Swedish Environmental Research Institute and SP Swedish National Testing and Research Institute. The methodology has been applied in several LCA studies and the methodology and the results have been presented in several fire related conferences and papers. A guideline for the methodology has also been developed (Andersson et al., 2004).

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Short description of the methodology

Fires occur often enough for statistics to be developed providing necessary information on material flows in the model. A model has been specifically developed to allow for this inclusion and will be referred to as the Fire-LCA model. The model itself is generally applicable, provided that appropriate additions and changes are made whenever a new case is studied.

The Life-Cycle Assessment methodology that has been developed is based on traditional LCA methodology. This methodology is described in the ISO standard 14040- series and other documents from different countries in Europe and the USA.

In a conventional LCA the risk factors for accidental spills are excluded. In the LCA data for the production of a chemical, for example, only factors during normal operation are considered. However, there can also be, for example, emissions during a catastrophic event such as an accident in the factory. Those emissions are very difficult to estimate due to a lack of statistical data and lack of emission data during accidents. The same type of discussion exists for electric power production in nuclear power plants. In the case of the evaluation of normal household fires the fire process can be treated as a commonly occurring activity in the society. The frequency of fire occurrences is relatively high (i.e. high enough for statistical treatment) and statistics can be found in most countries. This implies that it is possible to calculate the different environmental effects of a fire if emission factors are available. Statistical fire models can be set up for other types of fires but the uncertainty in the statistical fire model will increase as the statistical data is more limited.

The fundamental function of a better fire performance is to prevent a fire from occurring or to slow down the fire development. Improving a products fire performance will thus change the occurrence of fires and the fire behaviour. By evaluating the fire statistics available with and without different types of fire performance improvements the environmental effects can be calculated. The benefits of a higher fire performance must be weighed against the “price” society has to pay for the production and handling of possible additives and/or other ways of production. The LCA methodology will be used to evaluate the application of higher fire performance in society. In this way a system perspective is applied.

A Life Cycle Assessment model should be able to describe the LCA system as defined in the Goal and Scope of the study. In this case it should be able to describe the entire life cycle of a product with different fire performance. Schematically the LCA model proposed for a Fire-LCA can be illustrated as in Figure 9. The model is essentially equivalent to a traditional LCA approach with the inclusion of emissions from fires being the only real modification. In this model a functional unit is characterised from the cradle to the grave with an effort made to incorporate the emissions associated with all phases in the unit’s life-cycle. Thus, the model includes production of material for the product to be analysed, as well as the production of the additives if applicable e.g. different flame retardants. If possible the model should be designed in such a way that the fire performance can be varied. Furthermore, the model should include production, use and waste handling of the product during its lifetime. During the lifetime of the

products to be analysed, some products will be involved in different types of fires. The Fire-LCA mode
l will therefore include modules to describe the fire behaviour for the different types of fires. Fire statistics are used to quantify the amount of material involved in the different types of fires. In addition, the model should also include modules for handling the production of replacement materials that are needed due to the shortening of lifetime that the fires have caused. If possible the model should also include modules for the handling of the fire extinguishing process and the decontamination process.

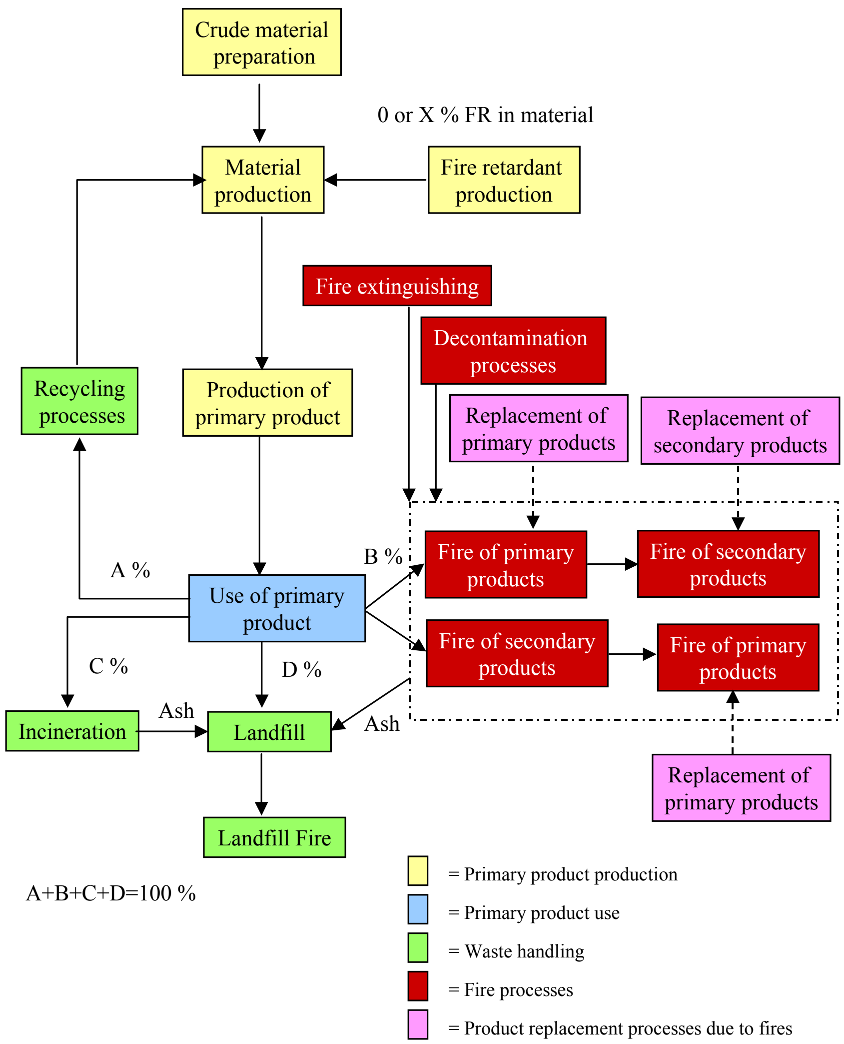

Figure 9: Schematic representation of the LCA model.

Appendix D: The thermodynamic basis of production and consumption

The earth differs from all other known planets by the presence of life. Life is undeniably the most important asset of the world. It is also one of the most puzzling ones. Biologists, claiming to have mastered the "science of life", have no answer to the basic question "what is life"? Erwin Schrödinger, incidentally one of the founding fathers of quantum theory in the 1920s and Nobel laureate in 1933, wrote in 1944 a semi-popular monograph with this title "What is life?". Below, we quote a crucial fragment.

LIVING MATTER EVADES THE DECAY TO EQUILIBRIUM

What is the characteristic feature of life? When is a piece of matter said to be alive? When it goes on 'doing something', moving, exchanging material with its environment, and so forth, and that for a much longer period than we would expect an inanimate piece of matter to 'keep going' under similar circumstances. When a system that is not alive is isolated or placed in a uniform environment, all motion usually comes to a standstill very soon as a result of various kinds of friction; differences of electric or chemical potential are equalized, substances which tend to form a chemical compound do so, temperature becomes uniform by heat conduction. After that the whole system fades away into a dead, inert lump of matter. A permanent state is reached, in which no observable events occur. The physicist calls this the state of thermodynamical equilibrium, or of 'maximum entropy'.

Practically, a state of this kind is usually reached very rapidly. Theoretically, it is very often not yet an absolute equilibrium, not yet the true maximum of entropy. But then the final approach to equilibrium is very slow. It could take anything between hours, years, centuries, … To give an example - one in which the approach is still fairly rapid: if a glass filled with pure water and a second one filled with sugared water are placed together in a hermetically closed case at constant temperature, it appears at first that nothing happens, and the impression of complete equilibrium is created. But after a day or so it is noticed that the pure water, owing to its higher vapour pressure, slowly evaporates and condenses on the solution. The latter overflows. Only after the pure water has totally evaporated has the sugar reached its aim of being equally distributed among all the liquid water available.

These ultimate slow approaches to equilibrium could never be mistaken for life, and we may disregard them here. I have referred to them in order to clear myself of a charge of inaccuracy.

IT FEEDS ON 'NEGATIVE ENTROPY'

It is by avoiding the rapid decay into the inert state of 'equilibrium' that an organism appears so enigmatic; so much so, that from the earliest times of human thought some special non-physical or supernatural force (vis viva, entelechy) was claimed to be operative in the organism, and in some quarters is still claimed.

How does the living organism avoid decay? The obvious answer is: By eating, drinking, breathing and (in the case of plants) assimilating. The technical term is *metabolism*. The Greek word (μεταβάλλειν) means change or exchange. Exchange of what? Originally the underlying idea is, no doubt, exchange of material. (E.g. the German for metabolism is *Stoffwechsel*.) That the exchange of material should be the essential thing is absurd. Any atom of nitrogen, oxygen, sulphur, etc., is as good as any other of its kind; what could be gained by exchanging them? For a

while in the past our curiosity was silenced by being told that we feed upon energy. In some very advanced country (I don't remember whether it was Germany or the U.S.A. or both) you could find menu cards in restaurants indicating, in addition to the price, the energy content of every dish. Needless to say, taken literally, this is just as absurd. For an adult organism the energy content is as stationary as the material content. Since, surely, any calorie is worth as much as any other calorie, one cannot see how a mere exchange could help.
What then is that precious something contained in our food which keeps us from death? That is easily answered. Every process, event, happening - call it what you will; in a word, everything that is going on in Nature means an increase of the entropy of the part of the world where it is going on. Thus a living organism continually increases its entropy - or, as you may say, produces positive entropy - and thus tends to approach the dangerous state of maximum entropy, which is death. It can only keep aloof from it, i.e. alive, by continually drawing from its environment negative entropy - which is something very positive as we shall immediately see. What an organism feeds upon is negative entropy. Or, to put it less paradoxically, the essential thing in metabolism is that the organism succeeds in freeing itself from all the entropy it cannot help producing while alive.

Since Schrödinger’s seminal work, the subject has been taken up by biologists and ecologists and other scientists as well (Schneider & Kay, 1994). Being alive means in thermodynamic terms: consuming a lot of negative entropy to maintain an organism far out of equilibrium. Prigogine and co-workers have extensively discussed the formation of complex self-organizing structures that are able to sustain themselves by feeding on a continuous inflow of low entropy.

This consumption of low entropy can only take place from outside the organism itself, or in other words, from the environment or the organism. This can only be done by increasing the entropy of this environment. Hence, life inevitably means degrading the environment. As Ulanowicz and Hannon (1987, p.183) remark: “life increases the amount of entropy generated in the universe.” This has natural repercussions with the limits within a sustainable world has to accommodate (Brozyna, 1997).

It thus appears that every form of life is necessarily associated with the extraction of low entropy resources, thereby producing an excess of entropy, thereby increasing the entropy of the world, and thereby deteriorating the overall quality of the world. The extent to which this implies a natural and inevitable degradation of the environment will be discussed later.

Appendix E: Inventory of existing methods and models

APPROACH/MODEL			AUTHOR(S)	PUBLICATION	REFERENCES
4.1 ISO LCA					
4.2 Other forms of LCA					
Hybrid IO-LCA			S. Suh	Functions, commodities and environmental impacts in an ecological–economic model	Ecological Economics 48 (2004) 451– 467
			Hertwich	A comment on "Functions, commodities and environmental impacts in an ecological–economic model"	Ecological Economics Vol: 59, Issue: 1, August 5, 2006
			Manfred Lenzen	A guide for compiling inventories in hybrid life-cycle assessments: some Australian results	Journal of Cleaner Production Vol: 10 Issue: 6, December, 2002 pp: 545-572
Integrated Hybrid Analysis			Sangwon Suh, Gjalt Huppes	Methods for Life Cycle Inventory of a product	Journal of Cleaner Production 13 (2005) 687e697
Dynamic			Pehnt	Dynamic life cycle assessment (LCA) of renewable energy technologies	Renewable Energy 31 (2006) 55–71
Regionalised	Regionalised Impact assessment	IO for LCIA	Norris, Gregory A	Life Cycle Emission Distributions Within the Economy: Implications for Life Cycle Impact Assessment	Risk Analysis 22 (5), 919-930

APPROACH/MODEL			AUTHOR(S)	PUBLICATION	REFERENCES
	Regionalised Impact assessment	Site dependent characterisation factors	Potting, J.,	Comparison of the acidifying impact from emissions with different regional origin in life-cycle assessment	Journal of Hazardous Materials, 61, 155–162
	meso-scale LCA methodology		Triacchini	Meso-scale life-cycle impact assessment of novel technology policies: The case of renewable energy	Journal of Hazardous Materials 78 2000 145–171
LCA for specific decision making context	attributional		Tilmann	Significance of decision-making for LCA methodology	Environmental Impact Assessment Review 20 (2000) 113–123
	consequential		Ekvall	Normative ethics and methodology for life cycle assessment	Journal of Cleaner Production 13 (2005) 1225e1234
	multi attribute value theory		Hämäläinen	How to benefit from decision analysis in environmental life cycle assessment (LCA)	European Journal of Operational Research 102 (1997) 279-294
Risk-based LCA			Khan	GreenPro-I: a risk-based life cycle assessment and decision-making methodology for process plant design	Environmental Modelling & Software 17 (2002) 669–692
Life-cycle modelling for design			Fitch, Peder	Life-cycle modelling for adaptive and variant design. Part 1: Methodology	Research in Engineering Design (2005) 15: 216–228

APPROACH/MODEL		AUTHOR(S)	PUBLICATION	REFERENCES
Sustainability in LCA		Lundqvist	The feasibility of including sustainability in LCA for product development	Journal of Cleaner Production 6 (1998) 289–298
Life cycle indexing system		Khan	Life cycle iNdeX (LInX): a new indexing procedure for process and product design and decision-making	Journal of Cleaner Production 12 (2004) 59–76
Environmental Activity Elasticities	LCA for Environmental Policy Analysis	Hondraki-Birbili	A Novel Methodology for Environmental Policy Analysis—The Concept of Environmental Activity Elasticities and an application to the CAP	Journal of Environmental Management (1996) 46, 255–269
4.3 Other Life Cycle Approaches				
energy analysis		Mario Giampietro	Energy Analyses as a Tool for Sustainability: Lessons from Complex System Theory	Annals of the New York Academy of Sciences Volume 879 TEMPOS IN SCIENCE AND NATURE: STRUCTURES, RELATIONS, AND COMPLEXITY Page 344 - June 1999
ecodesign	LC planning (ecodesign)	Kobayashi	Strategic evolution of eco-products: a product life cycle planning methodology	Research in Engineering Design (2005) 16: 1–16
	Env-QFD	Keijiro Masui, Tomohiko Sakao and Atsushi Inaba	Development of a DfE Methodology in Japan - Quality Function Deployment for Environment-	ECP Newsletter, 20, 1-6

APPROACH/MODEL	AUTHOR(S)	PUBLICATION	REFERENCES
Life Cycle Activity Analysis LCAA	Freire, F., Ferrão, P., Thore, S	Life cycle activity analysis: logistics and environmental policies for bottled water in Portugal.	OR Spektrum 23[1], pp. 159-182
exergy analysis	Finnveden	Exergies of natural resources in Life-cycle assessment and other applications	Energy Vol 22, No 9 pp923-931, 1997
	Bisio	Energy and exergy analysis of heat transformers with thermal sources and sinks of finite capacity	Energy Conversion Engineering Conference, 1996. IECEC 96. Proceedings of the 31st Intersociety Volume 2, 11-16 Aug. 1996 Page(s):719 - 724 vol.2
	Xiao Feng; Zhu, X.X.; Zheng, J.P.;	A practical exergy method for system analysis	Energy Conversion Engineering Conference, 1996. IECEC 96. Proceedings of the 31st Intersociety Volume 3, 11-16 Aug. 1996 Page(s):2068 - 2071 vol.3
Exergy accounting	Tiezzi	Exergy and extended exergy accounting of very large complex systems with an application to the province of Siena, Italy	Journal of Environmental Management Article in Press doi:10.1016/j.jenvman.2006.04.016
Comprehensive Environmental Assessment		Systematic Approach to Evaluating Trade-Offs among Fuel Options	Annals of the New York Academy of Sciences Volume 1076 Living in a Chemical World: Framing the Future in Light of the Past Page 498 - September 2006
Environmentally conscious planning of supply chain	Pistikopoulos	Environmentally conscious long-range planning and	Journal of Cleaner Production 13 (2005) 1428e1448

APPROACH/MODEL	AUTHOR(S)	PUBLICATION	REFERENCES
		design of supply chain networks	
LCC	Gerald Rebitzer, Stefan Seuring	Methodology and Application of Life Cycle Costing	Int J LCA 8 (2) 110 – 111 (2003)
	Gerald Rebitzer1, David Hunkeler	Life Cycle Costing in LCM: Ambitions, Opportunities, and Limitations. Discussing a framework	Int J LCA 8 (5) 253 – 256 (2003)
POEMS	Frank G. A. de Bakker	Product-Oriented Environmental Management. Lessons from Total Quality Management	Industrial Ecology Vol. 5, No. 2, Pages 55-69
Cumulative Energy Requirements Analysis (CERA)	Verein Deutscher Ingenieure (VDI) (Hrsg.)	Kumulierter Energieaufwand - Begriffe, Definitionen, Berechnungsmethoden.	Richtlinie VDI 4600, Beuth Verlag, Berlin
Material input per unit of service (MIPS)	M. Ritthoff, H. Rohn, C. Liedtke	Calculating MIPS. Resource productivity of products and services	Wuppertal Institute at the Science Centre North Rhine-Westphalia, 2002. ISBN 3-929944-56-1e
Material Intensity Analysis	Bringezu, S., Stiller, H., Schmidt-Bleek, F	Material Intensity Analysis - A Screening Step of LCA	Proceedings of the Second International Conference on EcoBalance, Nov. 18-20, 1996, Tsukuba, Japan, p.147-152
4.4 Macro and Meso Societal models			
Strategic Environmental Assessment	Måns Nilsson	Testing a SEA methodology for the energy sector: a waste incineration tax proposal	Environmental Impact Assessment Review 25 (2005) 1 –32

APPROACH/MODEL			AUTHOR(S)	PUBLICATION	REFERENCES
			Sheate	The EC Directive on Strategic Environmental Assessment: a much-needed boost for environmental integration	European Environmental Law Review Dec. 2003 p. 331
Input Output Analysis (IOA)			W. Leontief	Input-Output Economics	Oxford University Press, New York
			W. Leontief	Environmental repercussions and the economic structure: an input-output approach	Rev. Econ. Stat. 52, 262-271
EnvIOA				European Network of Environmental Input-Output Analysis	1st Meeting: 8 May 2001, Madrid, Spain. Proceedings
Environmental Impact Assessment			Matthew Cashmore*	The role of science in environmental impact assessment: process and procedure versus purpose in the development of theory	Environmental Impact Assessment Review 24 (2004) 403–426
Hierarchy theory and sustainable development			Mario Giampietro	Using hierarchy theory to explore the concept of sustainable development	Futures, Volume 26, Issue 6 , July-August 1994, Pages 616-625
Evolutionary Economic Theories			Peter Mulder & Jeroen C.J.M. van den Bergh	Evolutionary Economic Theories of Sustainable Development	Growth and Change Volume 32 Issue 1 Page 110 - Winter 2001
general economy models	computable general equilibrium models	GEM-CCGT			
		GEM-E3	Böhringer, C.	European Emission Mitigation Policy and	Final Report to the EC, Contract No. JOS3-CT97-0017

APPROACH/MODEL		AUTHOR(S)	PUBLICATION	REFERENCES
			Technological Evolution: Economic Evaluation with the GEM-E3-EG Model (GEM-E3-ELITE).	
	MacGEM	Johan Eyckmans, Denise Van Regemorter and Vincent van Steenberghe	Is Kyoto Fatally Flawed? An Analysis with MacGEM	ETE Working Paper 2001-18
	Global Trade Analysis Project (GTAP)	Peter Nijkamp *	Modelling the impacts of international climate change policies in a CGE context: The use of the GTAP-E model	Economic Modelling Volume: 22, Issue: 6, December, 2005, pp. 955-974
	WorldScan			
	SNI-AGE	Gerlagh, Reyer	A measure of sustainable national income for the Netherlands	Ecological Economics Volume: 41, Issue: 1, April, 2002, pp. 157 - 174
macro-economic model	NEMESIS	Dorothee Brecard	Macro-economic consequences of European research policy: Prospects of the Nemesis model in the year 2030	Research Policy Volume: 35, Issue: 7, September, 2006, pp. 910-924
	QUEST-II	Werner Röger and Jan in ’t Veld	Some selected simulation experiments with the European Commission’s QUEST model	EUROPEAN COMMISSION DIRECTORATE-GENERAL FOR ECONOMIC AND FINANCIAL AFFAIRS ECONOMIC PAPERS
	GINFORS			
	E3ME	Barker, Terry	Achieving a 10% cut in Europe's carbon dioxide emissions using additional excise duties: coordinated, uncoordinated and	Economic Systems Research, Vol. 11, No. 4, 1999, pp. 401-421.

APPROACH/MODEL			AUTHOR(S)	PUBLICATION	REFERENCES
				unilateral action using the econometric model E3ME,	
partial economic sector models	energy sector	POLES (Prospective Outlook on Long-term Energy Systems)	Patrick Criqui	POLES Prospective Outlook on Long-term Energy Systems	Unité mixte de recherche du Centre National de la Recherche Scientifique et de l'Université Pierre Mendès France (UFR DGES) - UMR 5111
		PRIMES			
		MARKAL	CES-KULeuven VITO	MARKAL, A MODEL TO SUPPORT GREENHOUSE GAS REDUCTION POLICIES	DWTC/SSTC Final Report
	agricultural sector	WATSIM			
		IMPACT	Mark W. Rosegrant, Siet Meijer, Sarah A. Cline	International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description	International Food Policy Research Institute, Washington D.C. - February 2002
		CAPRI	LEI, The Hague, Netherlands IAP, Institute for Agricultural Policy, University of Bonn, Germany IAM, Institute Agronomique Mediterranéen, Montpellier, France	Development of models and tools for assessing the environmental impact of agricultural policies	Final report (ENV.B.2/ETU/2000/073) Joint project of LEI, IAP and IAM The Hague, 27. April 2003
		RAUMIS	Weingarten, P.	Regionalisierte Agrar- und Umweltinformationssystem für die Bundesrepublik Deutschland(RAUMIS)	Berichte über Landwirtschaft, Bd. 73, S. 272 - 303.
	transport sector	TREMOVE	TRANSPORT & MOBILITY LEUVEN	TREMOVE Description of model and baseline	DRAFT REPORT European Commission DG ENV BU 9 1043

APPROACH/MODEL		AUTHOR(S)	PUBLICATION	REFERENCES
		VITAL DECOSTERSTRAAT 67A BUS 0001 3000 LEUVEN BELGIË	version 2.41	Brussels Belgium 3 March 2006
	TRENEN II			
	IMAGE	Alcamo, Joseph, Rik Leemans, Eric Kreileman (eds),	Global Change Scenarios of the 21st Century, Results from the IMAGE 2.1 Model.	Elsevier Science, Kidlington, Oxford, U.K. 1998, ISBN 0080434479.
	CLIMNEG	Eyckmans, Johan; Tulkens, Henry	Simulating coalitionally stable burden sharing agreements for the climate change problem	Resource and Energy Economics Volume: 25, Issue: 4, October, 2003, pp. 299-327
Endogenous growth models		David C. Maré	What Do Endogenous Growth Models Contribute?	Motu Working Paper 04–04 Motu Economic and Public Policy Research July 2004. ISSN 1176-2667.
Bio-physical models				
Climate models				
Material Flow Analysis (MFA)		Reinout Heijungs, Ester van der Voet	Practical Handbook of Material Flow Analysis, Advanced Methods in Resource and Waste Management , by Paul H. Brunner and Helmut Rechberger	Journal of Industrial Ecology Winter/Spring 2006, Vol. 10, No. 1-2: 293-294.
Substance Flow Analysis (SFA)		Ester van der Voet	Substances from cradle to grave. Development of a methodology for the analysis of substance flows through the economy and the environment of a region with case studies on	CML. 1996, Leiden University: Leiden.

APPROACH/MODEL	AUTHOR(S)	PUBLICATION	REFERENCES
		cadmium and nitrogen compounds.	
Environmental Risk Analysis	Ian Lerche, Evan K. Paleologos	Environmental Risk Analysis	McGraw-Hill Professional. ISBN: 0071372660
NAMEA	De Haan M., Keuning, S.J., Bosch., P.R.	Integrating indicators in a National Accounting Matrix including Environmental Accounts (NAMEA); an application to the Netherlands.	National accounts and the environment; papers and proceedings from a conference, London, 16–18 March, Statistics Canada, Ottawa.; 1994
	Steven J. Keuning, Jan van Dalen, Mark de Haan	The Netherlands' NAMEA; presentation, usage and future extensions	Structural Change and Economic Dynamics 10 (1999) 15–37
4.5 Combined models			
Sustainability Impact Assessment	Löschel	Computable general equilibrium models for sustainability impact assessment: Status quo and prospects	Ecological Economics Vol: 60 Issue: 1, November 1, 2006
Social-economic models	Fielding, David	Health and Wealth: A Structural Model of Social and Economic Development	Review of Development Economics Volume: 6, Issue: 3, October, 2002, pp. 393-414
Social Accounting Matrices	Kehoe	Social accounting Matrices and Applied general Equilibrium Models	Federal reserve Bank of Minneapolis research department. Working paper 563. Jan 1996
Social Accounting Matrices	Nigel Stuttard	Linking together economic and social data: using social accounting matrices to look at the distribution of earnings	Labour Market trends May 2003

APPROACH/MODEL		AUTHOR(S)	PUBLICATION	REFERENCES
Integrated Assessment Models (IAM)		S.H. Schneider	Integrated Assessment of global climate change: transparent rational tool for policy making or opaque screen hiding value-laden assumptions?	Environmental Modelling and Assessment 2, pp. 229-249
Eco-efficiency analysis		Gjalt Huppes and Masanobu Ishikawa	Eco-efficiency Analysis A Framework for Quantified	Journal of Industrial Ecology, Vol. 9, No. 4, Pages 43-46
Extended Social Accounting Matrix Vol: 16, Issue: 4, August, 2000		Xie, Jian	Environmentally extended social accounting matrix (ESAM)	Environmental and Resource Economics
4.6 Simplified models				
LCM	Corporate environmental performance evaluation	Shuangyu Xie	Corporate environmental performance evaluation: a measurement model and a new concept	Bus. Strat. Env. (in press) Published online in Wiley InterScience (www.interscience.wiley.com) DOI: 10.1002/bse.493
	Environmental accounting	Francois Friend	Environmental accounting: A management tool for enhancing corporate environmental and economic performance	Ecological Economics Volume 58, Issue 3 , 25 June 2006, Pages 548-560 doi:10.1016/j.ecolecon.2005.07.026
	Environmental Management Accounting (EMA)	Christine Jasch	Environmental Management Accounting Metrics, Procedures and Principles	Expert Working Group on “Improving the Role of Government in the Promotion of Environmental Management Accounting”, United Nations Division for Sustainable Development, New York (2001).
Social		Marc T. Jones	The Institutional	Journal of Business Ethics 20:

APPROACH/MODEL	AUTHOR(S)	PUBLICATION	REFERENCES
responsibility		Determinants of Social Responsibility	163–179, 1999.
	A.B.Carroll	Corporate Social Responsibility. Evolution of a Definitional Construct	Business and Society 33, 268-295
CBA		Cost-Benefit Analysis and the Environment. Recent Developments	ISBN 92-64-01004-1 – © OECD 2006
TCA	Centre for Waste Reduction Methodology (CWRT)	Total Cost Assessment Methodology	AIChe ISBN 0-8169-0807-9
Multi-Criteria Analysis (MCA)	Paruccini, M.	Applying Multicriteria Aid for Decision to Environmental Management,	Kluwer, Dordrecht. 1994