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Position paper on models and tools which may be related to LCA or might expand LCA

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Models and tools to consider

Position paper on models and tools which may be related to LCA or might expand LCA

Options for Broadening and Deepening LCA

Deliverable (D4) of work package 3 (WP3) CALCAS project

Harish Jeswani and Adisa Azapagic
School of Chemical Engineering and Analytical Science,
University of Manchester

Philipp Schepelmann and Michael Ritthoff
Wuppertal Institute for Climate and Energy

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1 Introduction

Life Cycle Analysis (LCA) has evolved significantly over the past three decades to become a systematic and consistent tool for identifying and quantifying potential environmental burdens and impacts of a product, process or an activity. It has become an invaluable decision-support tool that can be used by manufacturers, suppliers, customers, policy-makers and other stakeholders (Rebitzer *et al.,* 2004). For example, LCA results are valuable in making decisions regarding product development and eco-design at the design stage, production system improvements and process optimisation at the manufacturing stage, product choice at the consumer level and development and implementation of production and consumption policies. The recognition of LCA by governments, enterprises and non-governmental organisations has been confirmed in a preliminary assessment of user needs in Work Package 6. Despite that, application of LCA and its integration into decision-making process has not been as widespread as expected.

The CALCAS preliminary assessment of user needs confirms findings of Ansems *et al.* (2005) that limited access to data and complex procedures and software tools are major barriers for potential users. Further, the ISO 14044 methodology has often been considered too generic to be useful at the practical level; e.g. there is still no common agreement on system boundaries or allocation methods (Suh *et al.*, 2004). Moreover, the LCA results have a low spatial and temporal resolution (Udo de Haes *et al.*, 2004). Other governance aspects that have been raised in the CALCAS Work Package 4 include the inputs of policy for LCA, the integration of persistent environmental problems and inputs from LCA into politics.

To address these weaknesses and to increase the efficacy of sustainability decision making, some argue that there is a need to expand LCA framework by taking into account broader externalities, broader interrelations and different application/user needs with often conflicting requirements. There are two complementary potential approaches to expanding the LCA framework: "deepening" – improving ISO 14044 guidance related to definition of system boundaries, allocation methods, dynamic aspects, scenarios specification, etc. – and "broadening" – i.e. integration into LCA of social and economic dimensions of sustainable development (Azapagic and Perdan, 2000; Wrisberg *et al.*, 2002; de Ridder *et al.*, 2006; Wiedmann *et al.,* 2006). Its integration and connection with other concepts and methods could strengthen LCA as a tool and eventually increase its usefulness. However, expanding the LCA framework might lead to ever more complex LCA which could damage the reputation of the tool and eventually decrease its value for decision-makers in business and politics.

In view of these opportunities and risks, the Work Package 3 (WP3) of CALCAS aims to explore the potential options for deepening and broadening the LCA methodologies beyond the current ISO framework for improved sustainability analysis. By investigating several models and methods which are related to LCA, the WP3 will indicate options for incorporating (parts of) other models and methods or combining with other models and methods to expand LCA framework. However, before ways of deepening or broadening the existing LCA framework can be chosen, the various modes of LCA and related concepts, methods or models must be defined and analysed with respect to sustainability. Principal assumptions of different methods and models need to be formulated, and their strengths and weaknesses for assessing impacts on social, economic and environmental aspects of sustainable development need to be compared. These targets will be achieved through three deliverables: D4 (Position paper – Models and tools to Consider), D10 (Report on SWOT Analysis) and D17 (Final Report – LCA Broadened and Deepened options).

This paper is deliverable D4 of WP3. It reviews models and methods which are related to LCA to set the basis for the next stage, i.e. SWOT analysis. Building on the scoping of scientific trends in WP2 (D1) and governance requirements by WP 4 (D3), this paper appraises the demand for and supply of sustainability assessment approaches. It further explores the options for deepening and broadening LCA methodologies to meet the demand. To assess the political demand for LCA approaches, Section 2 reviews the policies, which influence application and development of LCA. Looking at the latest development on the supply side, Section 3 provides overview of various methods and assessment frameworks that relate to LCA in practice or could relate to LCA in theory. Section 4 discusses the options for broadening and deepening of LCA. The report concludes with recommendations for SWOT analysis of relevant methods.

2 Demand for Life Cycle Approaches

The demand created by the public discourse about sustainable development has been one of the major driving forces behind the increasing use of life cycle approaches. From high-level political strategies down to detailed technology and product choices, the ultimate question is always whether society is developing towards or away from sustainability. Therefore, the importance of life cycle approaches for sustainable consumption and production (SCP) has been emphasised in the Johannesburg Plan of Implementation. In Europe, LCA studies have been used to inform public decision making and its basic philosophy, life cycle thinking, has been enshrined in the principles such as '*the polluter pays*', '*producer responsibility*', and '*product stewardship*' that underlie the development of recent environmental policies in the EU.

This section discusses the most important policies, which are the main drivers for the increasing use of life-cycle and other assessment approaches.

2.1 International Policies on Sustainable Development

The 1992 Rio declaration on environment and development stated that '*states should reduce and eliminate unsustainable patterns of production and consumption*' (UN, 1992). Reaffirming this principle in 2002, the Johannesburg World Summit on Sustainable Development put a strong emphasis on the need to '*change unsustainable patterns of consumption and production*' (WSSD, 2002). The Johannesburg Plan of Implementation called for the fundamental changes in the way societies produce and consume to accelerate the shift toward sustainable consumption and production. It further called for the adoption of tools, policies, and assessment mechanisms based on life-cycle analysis to promote sustainable patterns of production and consumption and to increase the eco-efficiency of products and services. LCA has already been proven a useful tool in advancing the agenda of sustainable production. However, sustainable consumption requires analysis that extends beyond traditional LCA, hence LCA in that context has been little used (Hertwich, 2005). Although in principle LCA can inform consumer and policy decisions on environmental grounds, some argue that it would need to be combined with economic and sociological assessments to fully inform decision making (Hertwich, 2005).

2.2 EU Policies on Sustainable Development

The EU Sustainable Development Strategy (SDS) agreed in 2001 and renewed in 2006 defines the widest frame for policy-making in the EU (Council of the European Union, 2001; Council of the European Union, 2006). The renewed EU SDS, which addresses seven key challenges for sustainable development, particularly emphasises the need for impact assessment in order to evaluate the major policy decisions in relation to economic, social and environmental dimensions of sustainable development. It also calls for adoption of such methods by the member countries when developing their strategies, programmes and projects. The guidelines for impact assessment suggest a list of tools which could be used as an aid to the impact assessment process (CEC, 2005a). Separate tools are suggested for assessing economic, social and environmental impacts, while use of cost-benefit analysis (CBA), risk assessment (RA), and multi-criteria decision analysis (MCDA) are listed as methods for comparing the impacts. However, the selection of tools and the extent to which the selected tools could be used in the actual impact assessment is at the discretion of the Commission desk officer. Application of life-cycle thinking is specifically suggested for the development of policies related to sustainable consumption and production and conservation of natural resources.

There are various EU policies which address different aspects of sustainable development as identified under the key challenges in the renewed SDS. However, an explicit need for assessment tools is emphasised in environmental policies related to production and consumption. Among policies that directly target production and consumption patterns is the landmark Communication on Integrated Product Policy (IPP), which was published in June 2003 (CEC, 2003). It seeks to minimise the environmental effects of a product by looking at all phases of a product's life cycle and taking action where it is most effective. IPP recognises life cycle thinking as an important contribution to coherent, science-based decision making. More specifically, the included instruments, such as environmental labelling, environmental product declarations and green public procurement, require life-cycle data for carrying out impact assessments of products. Therefore, LCA is considered as one of the important supporting tools for implementation of IPP. However, IPP and the other instruments do not specifically require assessment of economic and social aspects related to products. Likewise, very little attention is paid in IPP to sustainable sourcing of products and services (Mont and Bleischwitz, 2007).

However, recognising LCA's limitations, Communication on IPP also emphasised the need for more consistent data and consensus on LCA methodologies. To promote the use of LCA, the Commission has initiated various initiatives. These include: availability and access to life-cycle information of products, exchange of best practices on LCA, improving the coordination between various tools including EMS and environmental labelling. The Commission, through the EU Platform on LCA[1], is developing the International Reference Life Cycle Data System (ILCD), which will ensure a common set of quality, method, documentation, nomenclature and review requirements for different LCA applications. The ILCD includes also the ELCD (European Life Cycle Database), which provides a number of life cycle inventory data sets of the most common goods and services representing the EU scenario and supported by relevant industry associations.

[1] http://lca.jrc.ec.europa.eu/

In December 2005, the IPP Communication was strengthened by the European Commission's Thematic Strategy on the Sustainable Use of Natural Resources (TSURE) (CEC, 2005b). Its focus is on decoupling economic growth from environmental impacts and aims to increase the resource productivity rate to at least 3% p.a. To achieve these aims, the strategy calls for better knowledge of environmental impacts as well as of business opportunities. Such a knowledge base will be created with the help of a European Data Centre and an international panel on sustainable resource management. Life cycle thinking is a core to this thematic strategy, being a foundation of the indicators that will be developed to monitor progress across the community. Great importance is attached to the non-legislative approach of IPP, but also to the Environmental Technologies Action Plan (ETAP)[2] in the strategy.

As shown in Figure 1, the demand for physical assessment approaches is characterised by two main concepts, differentiated in the TSURE (Schepelmann *et al.*, 2006):

- Resource productivity: De-coupling the use of natural resources and economic growth (e.g. dematerialisation also connected to a large extent to energy efficiency);
- Eco-efficiency: De-coupling environmental impacts and economic growth (for impact and problem-oriented policies, e.g. decarbonisation, detoxification).

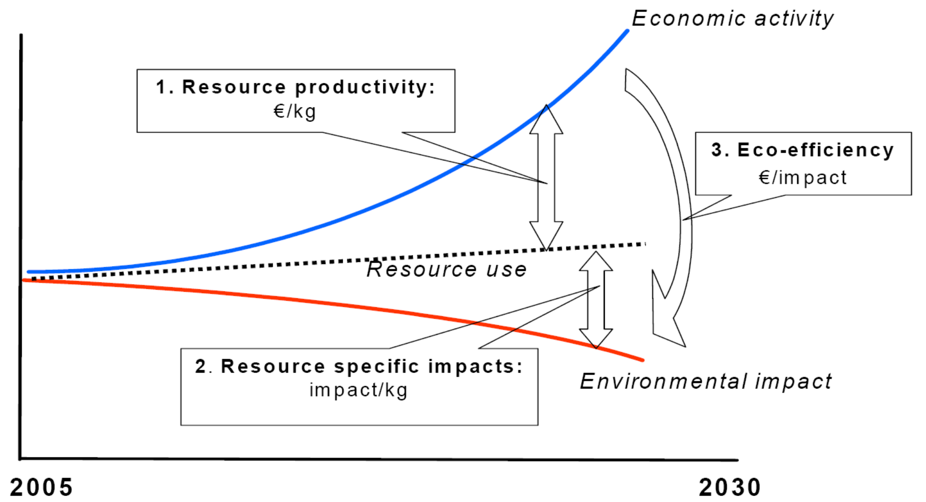

Figure 1: Decoupling economic activity, resource use and environmental impact
(Source: CEC, 2005c)

In parallel to the TSURE, the 2005 Thematic Strategy on the Prevention and Recycling of Waste also proposed consideration of the full implications of decisions from a life cycle perspective (CEC, 2005d). This placed environmental improvement further at the

[2] The overall aim of the ETAP project is to exploit the potential of environmental technologies for meeting the environmental challenges while contributing to competitiveness and growth (CEC, 2004).

heart of European waste policy, through proposals to update the Waste Framework Directive.

Incorporation of life-cycle thinking in policies has prompted the focus on specific areas. For example, recycling and recovery targets have been set for some key waste flows, i.e. packaging, end-of-life vehicles (ELVs), eco design of energy-using products (EuP) and waste electrical and electronic equipment (WEEE) under the respective directives using life cycle thinking. Moreover, these directives explicitly require the use of LCA and other tools. For example, Packaging and Packaging Waste directive (94/62/EC) states "*life-cycle assessments should be completed as soon as possible to justify a clear hierarchy between reusable, recyclable and recoverable packaging*''. The revised Packaging Directive (2004/12/EC), which sets recycling and recovery targets, requires taking account of life-cycle assessments and cost-benefit analysis results, for setting up recycling targets for each specific waste material. For this application, LCA should be able to describe the non-linear relationship between recycling rates and environmental impacts (Ekvall *et al.*, 2007). Likewise, under the EuP directive (2005/32/EC), manufactures of EuP are required to assess environmental, technological and economic impacts at the design stage.

ELV and WEEE directives (2005/32/EC & 2002/96/EC) encourage designers to develop products with recycling in mind. As the ELV directive requires car manufacturers to pay all or a significant part of the costs of taking back all cars sold after 2002, it is likely that not only the car manufacturers, but also the suppliers of components and material will need to identify and correct hot spots in the life cycle to minimise environmental impacts and costs at disposal. Similarly to meet the WEEE requirements, manufacturers of electrical and electronic equipment have to consider the environmental impacts and associated costs of disposing or recycling these items and materials contained in them. LCA is a useful tool in conducting these analyses.

The proposed amendments for the EU Fuel Quality directive (98/70 EC) also introduce life-cycle environmental criteria for fuel production (CEC, 2007). Furthermore, the proposal suggests mandatory reporting and monitoring of 'life-cycle greenhouse gas emissions' from transport fuels.

Besides using LCA for implementation of policies, information from LCA supports setting criteria for products and technologies within various policy frameworks, such as ETAP, EuP and green public procurement. Furthermore, EC considered a CBA and LCA to evaluate existing schemes and to evaluate the environmental impacts and benefits of various schemes and scenarios respectively in the process of updating the waste directive targets (Rebitzer *et al.*, 2004).

3 Supply of Life Cycle Approaches

3.1 Overview of Methods

This section provides an overview of various assessment frameworks and methods that relate to LCA in practice or could relate to LCA in theory. Table 1 presents the list of methods which are discussed here. Earlier overviews of sustainability and/or environmental assessment methods and tools have demonstrated that approaches can be categorised based on numerous factors or dimensions (Finnveden and Moborg, 2005; de Ridder, 2006; Ness *et al.*, 2007). Here, the methods are first broadly grouped based on their type, i.e. procedural frameworks and analytical methods. The focus of procedural frameworks is on procedures to guide the process to reach and implement environmental decisions, whereas analytical methods provide technical information for a better-informed decision making by modelling the system in a quantitative or qualitative way (Wrisberg *et al.*, 2002). The methods in these categorises are discussed and differentiated with respect to their characteristics such as coverage of sustainability dimensions (environment, economic and social) and focus (product, project or policy level). The list is, of course, not exhaustive but is indicative of the categories of different methods related to LCA. Review of models, software packages and databases is beyond the scope of this paper.

3.1.1 Procedural Methods / Assessment Frameworks

The assessment frameworks discussed here include Environmental Impact Assessment (EIA), Strategic Environmental Assessment (SEA) and Sustainability Assessment (SA). These are forecasting procedural methods which are used *ex-ante* to support the decision-making process for policies and projects (Finnveden and Moborg, 2005). In practice, various analytical methods (see Section 3.1.2) are applied as part of the assessment process.

(i) Environmental Impact Assessment (EIA):

EIA is generally used as a tool to ensure environmental and social impacts are considered explicitly both during the design of a new development and in the project authorisation decision (Cashmore, 2004). It is used as an aid to public decision making on larger projects.

Unlike LCA, which is time and location-independent assessment of potential impacts in relation to an entire production system, EIA is a procedural tool for evaluation of local environmental impacts, which generally takes into account the time-related aspects, the specific local geographic situation, and the existing background pressure on the environment (Tukker, 2000). Besides, EIA considers both quantifiable and non-quantifiable attributes.

Table 1: Assessment Models and Methods related to LCA

Models and Methods	Focus	Sustainability Dimensions	Key References
Procedural Methods (Assessment Frameworks)			
Environmental Impact Assessment (EIA)	Project	Environmental and social	Cashmore (2004); Tukker (2000)
Strategic Environmental Assessment (SEA)	Policy	Environmental and social	Nilsson *et al.* (2005); Ehrhardt and Nilsson (2006)
Sustainability Assessment (SA)	Policy	Environmental, economic and social	de Ridder (2006); Gibson, *et al.* (2005); SustainabilityA-Test project website
Analytical Methods			
Material Flow Analysis (MFA)	Policy, plan	Environment (natural resources)	Brunner and Rechberger (2004); Eurostat (2001)
Substance Flow Analysis (SFA)	Specific substance	Environment (natural resources)	van der Voet (2002)
Integrated LCA and SFA	Product/process/ service/ policy/ substances	Environment	Azapagic *et al.* (2007); van der Voet *et al.* (2005); Kleijn *et al.* (1997)
Material Input Per unit of Service (MIPS)	Product/ service	Environment (natural resources)	Ritthoff *et al.* (2002)
Energy/Exergy Analysis (EA)	Product/ service	Environment (natural resources)	Finnveden and Östlund (1997); Please refer D7 Calcas Report for other references.
Environmental Extended Input Output Analysis (EIOA)	Policy, product	Environment	Suh and Huppes (2005); European Network of EIOA (2001)
Risk analysis (RA/ERA/HERA)	Product/ service	Environmental and health impacts	Cowell *et al.* (2002); Calow (1998); Fairman *et al.* (1998)
Life Cycle Optimisation	Process/product	Integration of environmental and economic criteria	Azapagic (1999); Azapagic and Clift (1999)
Sustainable Process Design (SPD)	Process	Includes all sustainability dimensions	Azapagic *et al.* (2006)
Hybrid LCA	Product/ service	Environment	Suh and Huppes (2005); Suh (2004)
Life Cycle Costing (LCC)	Product/ service	Economics	Rebitzer and Seuring (2003); Udo de Haes *et al.* (2004); Also please refer D7.
Cost-Benefit Analysis (CBA)	Policy/ project	Economics (includes cost of environmental and social impacts)	OECD (2006)
Total Cost Accounting (TCA)	Product/ service	Economics (environmental costs)	CWRT (2000)
ExternE	Product/ service	Economics (environmental and energy costs)	ExternE (2005)
Eco-Efficiency Analysis (EEA)	Product/ service	Integration of environmental and	Huppes and Ishikawa (2005); Bleischwitz and

Models and Methods	Focus	Sustainability Dimensions	Key References
		economic	Hennicke (2004); WBCSD (2000)
Partial Equilibrium Models	Product/ service	Part of calculations to assess all dimensions	Case and Fair (1999)
Multi-Criteria Decision Analysis (MCDA)	Policy	Decision-support tool which can include all sustainability dimensions	DTLR (2001)

(ii) Strategic Environmental Assessment (SEA):

SEA is similar to EIA but tends to operate at a "higher" level of decision-making (i.e. for strategies and policies). Since SEA is conducted at an early stage, it is normally performed in conditions involving less information and high uncertainties (Ness *et al.*, 2007). SEA application in Europe is mostly found during policy development, leading to policy selection. However, the adoption of the EU SEA Directive is now forcing way for enhanced SEA implementation throughout the EU (Ehrhardt and Nilsson, 2006).

Within the SEA framework a range of different analytical tools and methods can be applied including RA, LCA, CBA and MCDA (Finnveden *et al*., 2003; Nilsson *et al*., 2005). With respect to time horizon, SEAs can be as retrospective or prospective as the tools used within their framework. By presenting such a framework, SEA facilitates environmental as well as broader sustainability policy integration in every political or strategic decision (Ehrhardt and Nilsson, 2006). However, like EIA, SEAs especially in Europe, have tended to focus on environmental impacts related to emissions of pollutants and some social aspects.

(iii) Sustainability Assessment:

Sustainability Assessment is an umbrella term that includes a range of methods and tools that may be known as 'sustainability appraisal', 'sustainability impact assessment', 'integrated sustainability assessment', or 'integrated assessment', amongst others.

More recently, the EU has introduced the more comprehensive method of (Sustainability) Impact Assessment. The intention is to move from the sectoral and often fragmented assessments to an integrated assessment covering environmental, economic and social parameters. The goal of this new tool is to be able to identify the likely positive and negative impacts of proposed policy actions - notably those relevant under the EU Sustainable Development Strategy - and thus enable informed political judgements about the proposal (CEC, 2002).

Although in principle this correlates with a 'sustainability approach', recent evidence suggests that sustainability concerns have in effect had difficulties competing with business, economic and competitiveness concerns, not least in the applications made in the European Commission (de Ridder *et al.*, 2006). As a relatively immature procedure, the institutional checks and balances are not in place yet, such as evaluation, quality control of the assessment. However, internet-based software (IQ TOOLS) has been developed to support the impact assessment process within the European Commission by strengthening its qualitative and quantitative tools and methods (Tamborra, 2005). Furthermore, as part of FP6, three other research projects: SustainabilityA-Test, MATISSE, and FORESCENE, have investigated options and developed analytical frameworks for sustainability assessment. These projects are outlined below:

> ***Sustainability A-Test Project:*** The purpose of this project was to strengthen integrated assessments for sustainable development by scientifically underpinning the use of assessment tools. Instead of developing new tools, it concentrated on already existing tools and their contribution to assessment process, i.e. to strengthen the analysis. The project investigated various tools in relation to their applicability for sustainable development assessments. The evaluation criteria included the suitability of assessment tools to support the various steps of policy processes, their ability to cover the key aspects of sustainable development (e.g. environmental, social and economic impacts, and cross-cutting issues like intergenerational aspects). These tools are broadly grouped into assessment framework, participatory tools, scenario tools, MCDA tools, CBA tools, accounting tools, physical analysis tools and models. Detailed information on specific tools can be found on the project's website[3].

> ***MATISSE (Methods and Tools for Integrated Sustainability Assessment) Project:*** This project is working on the development of an Integrated Sustainability Assessment framework for more sustainable Europe[4]. The main task of the project is to develop, test and demonstrate new and improved methods and tools for conducting Integrated Sustainability Assessment (ISA). The project is due to finish in March 2008 and thus no specific guidelines or experiments for conducting ISA exist yet. However, there are several studies carried out by the MATISSE research group which suggest that it is likely to be most useful for strategic and complex policy processes rather than more routine regulatory processes.

> For example, the report no. 16 (Lotze-Campen, 2007) evaluates modelling tools that have been applied to aspects of sustainable development and sustainability assessment. The focus has been on "applied" models, i.e. models that try to simulate real-world processes based on or calibrated to empirical information

[3] http://ivm5.ivm.vu.nl/sat/
[4] http://www.matisse-project.net/projectcomm/

(Table 2). Pure theoretical or conceptual models dealing with basic mechanisms without direct link to empirical information are not included. The models are grouped into three categories (biophysical, socio-economic and integrated) with 11 sub-categories (see Figure 2).

Table 2: Modelling tools for Integrated Sustainability Assessment (ISA) in MATISSE

Biophysical models	
Climate	GCM (HadCM, ECHAM)
	EMIC (CLIMBER, MAGICC/SCENGEN)
Hydrology	WaterGAP, SWIM, IRM-ABM
Biogeochemistry	LPJ, VECODE, 4C, WOFOST, ACCESS
Socio-economic models	
General economy	GE (GTAP, WorldScan, GEM-CCGT, GEM-E3, SNI-AGE)
	Macroeconometric (E3ME, NEMESIS, QUEST-II, GINFORS)
Partial economic sectors	Energy (POLES, PRIMES, MARKAL); Agriculture (WATSIM)
	IMPACT, CAPRI, RAUMIS); Transport (TREMOVE)
Demography	PHOENIX, IIASA Population Project
Public Health	MIASMA, PHSF, TARGET
Integrated models	
Land use change	FARM, AgLU, MAgPIE, CLUE, SFARMOD, CORMAS
Qualitative systems analysis	SYNDROMES, QSA-SCENE
Integrated assessment	IMAGE, ICLIPS, FUND, MIND, DEMETER, RICE-FEEM
	GENIE, IMPACT-WATER
Scenario Building and Planning	QUEST, POLESTAR, THRESHOLD-21, FAIR

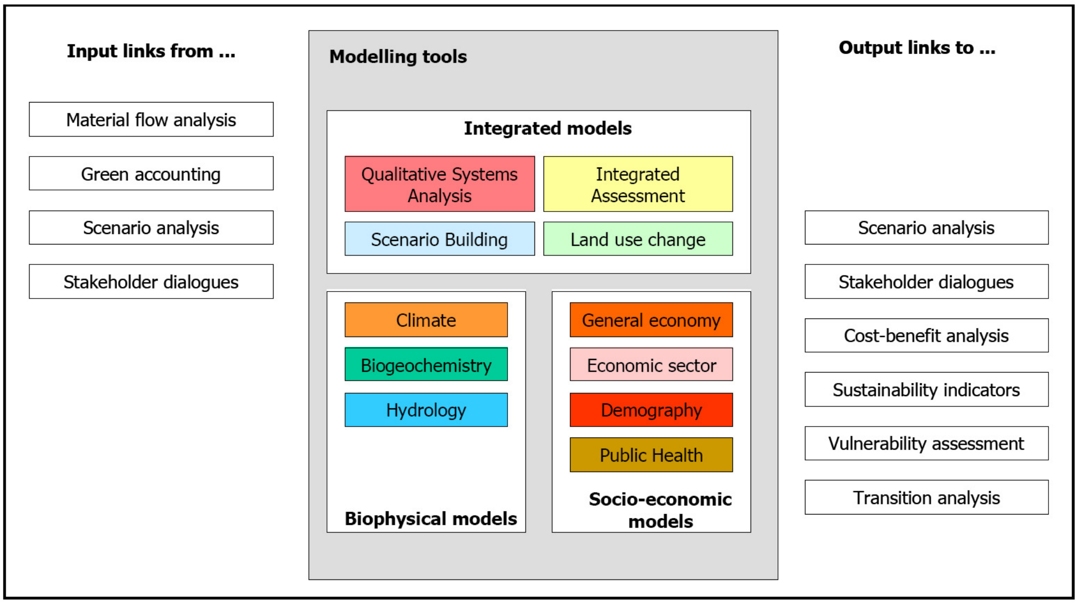

Figure 2: Modelling tools and their links to other tools for ISA in MATISSE

> ***FORESCENE:*** This project is developing an analytical framework for consistent environmental sustainability scenario building (forecasting, backcasting, simulation) in areas such as water, soil, biodiversity, waste and natural resources. It aims at developing a robust and scientifically sound framework to help develop harmonised middle and long-term (2015-2030) baseline and alternative policy scenarios[5].
>
> In the three problem areas 'water', 'biodiversity, soil and landscape', and 'resource use and waste', key drivers behind environmental problems have been identified, with a particular focus on cross-cutting drivers, i.e. influencing the three environmental topics. In order to define essential elements of a desired future, FORESCENE has shifted the perspective from the problem-oriented towards analysis of intervention areas (economic sectors, policy areas) such as agriculture, infrastructure/land use, and industry/economy. Integrated Sustainability Scenarios (ISSs), developed in a participatory process will be used to analyse the options for parameterisation and simulation/modelling. The operationalisation and parameterisation of the framework should then be transferred into a meta-model for sustainability assessment.

Therefore, the above frameworks, while not directly linked with LCA, could in theory be related to the tool in the broad context of sustainability assessments.

[5] www.forescene.net

3.1.2 Analytical Methods

Methods under this category include those which are used to identify and analyse the environmental, social or economic impacts related to policies, projects, products and substances. Most of these methods primarily focus on one particular sustainability dimension, while there are some methods that integrate two or more sustainability aspects.

3.1.2.1 Environmental Methods

Some of the environmental analysis methods are mainly concerned with natural resources such as Material Flow Analysis (MFA), Substance Flow Analysis (SFA), Energy/Exergy Analysis (EA), Material Input Per unit of Service (MIPS), Cumulative Energy Requirements Analysis (CERA) and Environmental Extended Input Output Analysis (EIOA), while other methods such as Risk Assessment (RA), focus on the impacts of products or services. LCA on the other hand includes both natural resources and impacts.

Life Cycle Optimisation, Sustainable Process Design (SPD), Integrated LCA and Substance Flow Analysis (SFA) and hybrid approaches apply LCA in combination with other methods. Other differences among these methods include scope (national, regional, sector, etc), application (product, project or policy), etc. These are discussed below.

(i) Material Flow Analysis:

Material Flow Analysis (MFA) represents a systematic accounting of the flows and stocks of a material within an economic system (Brunner and Rechberger, 2004). It provides an overview of material inputs into and outputs of an economy (Eurostat, 2001).

The Eurostat guide divides material flows into three categories; input, output and consumption indicators. Material input indicators illustrate the material inflows into the economy through local consumption and production whereas material output indicators quantify all material outflows back to the environment in terms of emissions and wastes. Material consumption indicators, on the other hand, calculate the total of all materials used in an economy (Ness *et al.*, 2007).

Within the three dimensions of sustainability, EMFA addresses foremost the environmental topics particularly well, although not every single topic is covered. Apart from the determination of equitable shares of global resource consumption, EMFA is not suitable to cover social topics. Economic topics may be covered partially (SustainabilityA-Test, 2005). MFA data can be used by other methods, which require quantitative units and indicators such as multi criteria decision analysis (MCDA) and environmental appraisal tools. MFA can also be regarded as a method to establish LCA inventory (Brunner and Rechberger, 2004; Azapagic *et al.*, 2007). However, it must be noted that MFA is directed towards reducing the number of substances of study as much as possible to maintain transparency and manageability, while LCA aims for completeness in assessing as many as possible substances and compounds (Brunner and Rechberger, 2004).

(ii) Substance Flow Analysis (SFA):

SFA is a specific type of MFA method, dealing only with the analysis of flows of chemical substances or compounds of special interest through a defined system. The core principle of SFA is the mass balance principle, derived from the law of mass conservation. It provides systematic, physical and quantitative information about the key stocks and flows of a specific substance or substances, about possible imbalances in the stocks and flows and about unsustainable use of resources. The general aim of the most SFA studies is to provide the relevant information for region's management strategy regarding specific chemicals (van der Voet, 1966; 2002). SFA could be used for analysing a product life cycle (Azapagic *et al.*, 2007) but it is often used for analysing industries (Ness *et al.*, 2007).

(iii) Integrated LCA and SFA:

This method combines both LCA and SFA (Kleijn *et al.*, 1997) in an integrated framework. It simultaneously tracks substances of interest in the environment and provides life cycle assessment of human activities from which those substances originate. More recently this method has been applied to mapping pollution from products, processes and activities in the urban environment (Azapagic *et al.*, 2007) and for mapping pollution from the main material flows (van der Voet *et al.*, 2005). The method makes a distinction between the 'foreground' and 'background' environment, enabling tracking of substances and their impacts in the area of immediate interest ('foreground') and in the rest of the life cycle of an activity ('background). In this way, the integrated method can be used to support decision making at the local, regional and wider levels. For example, the method can be useful for local authorities, local industry or citizens as well as for setting and implementing regional or national policies.

(iv) Material Input Per unit of Service (MIPS):

MIPS employs a life-cycle perspective to measure the total mass of flow of materials from cradle to cradle (extraction, production, use, waste/recycling) of a define service unit or product (Ritthoff *et al.*, 2002). Like LCA, MIPS is used for product or service assessment. Hence it often represents a screening method of LCA, focussing on the input side of the inventory and aggregating the results to three to five major categories: abiotic materials, biotic materials, soil/earth translocation, water extraction, and air input;

this input is related to the use, utility, function or service of a product. A practical application of the MIPS concept is called material intensity analysis. Material intensity analyses are conducted on the micro-level (focusing specific products and services), as well as on the macro-level (focusing national economies) (Ritthoff *et al.*, 2002). MIPS plays an important role in the discussion about dematerialisation or eco-efficiency.

(v) Energy/Exergy Analysis (EA):

Energy analysis is also a family of different methods which focus on all energy flows in an economy. Like SFA, Energy Analysis is also conducted according to the LCA or Input–Output Energy Analysis methodologies. Energy analysis can also be carried out by using different types of energy measures, such as exergy – a measure of the maximum amount of work that can be theoretically obtained (Brunner and Rechberger, 2004). An exergy analysis gives an overview of the effectiveness of resource utilisation, shows where losses occur and where technological improvements can be made to improve energy efficiency. Since exergy aggregates materials and energy to one final exergy quantity, it can be used as an indicator for sustainability assessment (Finnveden and Östlund, 1997). In addition, exergy can be calculated theoretically for all materials and energy flows, hence it can be applied to any material balance and may be used as an evaluation technique for a number of different objects. The exergy results can also be used in more approximate calculations such as in streamlined or simplified LCA where the aim is to identify critical areas of the life cycle (Finnveden and Östlund, 1997). However, the usefulness of exergy analysis is questionable for non-energy systems. Many users also find it difficult to estimate and interpret the meaning of exergy.

Another method, which has been developed to consider the upstream energy flows when optimising production processes, is Cumulative Energy Requirements Analysis (CERA). CERA is used to quantify the life cycle primary energy requirement for products and services (Wrisberg *et al.*, 2002). The cumulative energy requirement indicates a basic environmental pressure associated with the use of energy. Like material intensity the energy intensity cannot be used to quantify specific environmental pressures. It can be used to quantify the energy intensity of products, services and national economies; analyse options for energy savings in industry; and provide energy input coefficients for base materials to support engineering and design of products.

(vi) Environmental Input-Output Analysis / Environmental Extended Input Output Analysis (EIOA):

Input-Output Analysis (IOA) is a well-established analytical method within economics and systems of national accounts for national and regional studies (Finnveden and Moberg, 2005). It describes mutual deliveries between sectors in terms of money or in terms of volumes of goods. In general, the IOA calculates the total input requirements for a unit of final demand. It is mostly used to obtain a picture of the structure of the national economy and the mutual relations between economic sectors, and to identify the major flows of money and/or goods within the economic system.

EIOA includes environmental impacts either by adding emissions coefficients to the monetary IOAs or by replacing the monetary input-output matrixes with matrixes based on physical flows. The EIOA model provides the possibility to include a lot of different environmental indicators like air emissions, waste, energy input, material input, land use, and so on (also social aspects, such as employment can be integrated) (Finnveden *et al.*, 2003). The emissions most often included are the traditional air pollutants, but in some applications more pollutants have been included giving results similar to LCAs.

EIOA determines the overall environmental impact of an entire sector of the economy and may be viewed as a macro-level LCA covering the “cradle to gate” portion of the life-cycle. EIOA’s limitations are that it assumes an identical production technology of imported products and the domestic economy, homogeneity (each sector produces a single product) and a single technology in the production process. Also in EIOA, the attribution of environmental loads to sectors, products and services is proportional to the economic flows. However, as a method for environmental impact analysis (or LCA at the macro or national level), it has some advantage over LCA as it captures all the intra-sector flows, both direct and indirect, without “double-counting” (Flemmer and Flemmer, 2007). Therefore, it is potentially more useful to support high-level (e.g. national) policy decision-making rather than for decision making on specific products or activities.

Recently, it has been recognised as an important method to support Life Cycle Inventory (LCI) (Suh and Huppes, 2005). Several successful applications of EIOA have already been reported and its possibilities and areas of applications are still broadening (see the section on Hybrid LCA). In a policy context, EIOA has a further advantage as compared to LCA because it links with economic aspects.

(vii) Risk Assessment (RA):

Risk assessment is used in a wide range of professions to examine risks of different nature. It is also commonly used in assessing the environmental, health and safety related risks posed by chemicals, harmful substances, industrial plants, etc. Environmental Risk Assessment (ERA) is usually used as an umbrella term covering Human Health Risk Assessment (HRA), Ecological (or eco-toxicological) Risk Assessment and specific industrial applications of risk assessment that examine endpoints in people, biota or ecosystems (Calow, 1998). The RA approach is fundamental in development of EU policies and regulations for chemical, radiological and microbiological hazards.

Although the foundations of environmental risk assessment methodologies have traditionally been based on the investigation of effects on human health, the methodologies have also been expanded to examine the threats to ecosystem. The risks examined in the assessment can be physical such as radiation, biological such as a genetically modified organism or a pathogen, or chemical such as an immuno-toxic substance (Fairman *et al.*, 1998). In principle the process involves identifying the risk, assessing the risk in qualitative and/or quantitative ways, finally leading to a certain management decision for minimising that risk (Fairman *et al.*, 1998; Ness *et al.*, 2007). Data generated from RA are useful in the assessment component of LCA, especially toxicity (Olsen *et al.*, 2001).

Like LCA, RA is an analytical method used to support decision making in environmental management; however the following are the key differences between LCA and RA (Cowell *et al.,* 2002):

- RA focuses on a specific harmful endpoint arising from product, process or event and their occurrence in specified scenarios;
- unlike LCA, the absolute magnitude of a product or activity is very important in RA;
- In RA site-specific impact modelling is feasible as it is concerned with objects located at one or limited number of sites; and
- RA results are defined in time and hence provide information concerning the timing of impacts, which is not possible with LCA.

(viii) Life Cycle Optimisation:

This approach establishes a link between the economic and environmental performance of a process or product from ‘cradle to grave’ by combining multiobjective optimisation with LCA (Azapagic, 1999; Azapagic and Clift, 1999). Carrying out an LCA study of the system is the first step in the procedure. The results of LCA along with other socio-economic and technical constraints are used as an input into the optimisation model which is formulated in the next step. Using suitable multiobjective optimisation techniques, the system is optimised simultaneously on a number of environmental and economic objective functions. Finally, the best compromise alternative is chosen from a range of Pareto optimum solutions preferably by using a suitable multi-criteria decision making technique.

(ix) Sustainable Process Design (SPD):

Underpinned by lifecycle thinking, the objective of this method is to integrate technical, economic, environmental and social criteria during the different stages of process design (Azapagic *et al.*, 2006). In SPD environmental sustainability is assessed within an extended system boundary drawn from ‘cradle to grave’ using LCA as a tool. For most of the process-relevant social sustainability criteria, the method proposes quantitative indicators such as number of employees, occupation exposure limits, potential safety risks from fire and explosion. Economic criteria include the usual micro-economic aspects (capital and operating costs, NPV etc.) and macro-economic issues (e.g. contribution to GDP, value added etc.).

(x) Hybrid Approaches:

Hybrid analysis offers the possibility of combining IO-LCA's strength of being complete with product-LCA's strength of being detailed (Udo de Haes *et al*., 2004). Hybrid approaches in general provide more complete system definition, while preserving specificity with a relatively small amount of additional information and inventory data (Rebitzer *et al.,* 2004). Hence the combination promises to reduce data collection effort and avoid cut-off errors inherent in process-LCA (Hertwich, 2005).

Suh *et al.* (2004) distinguish three different hybrid approaches, namely, tiered hybrid analysis, input output-based hybrid analysis, and integrated hybrid analysis. Generally, the input output-based hybrid approach is carried out by disaggregating industry sectors in the input-output table, while the tiered hybrid method is applied for the use and end-of-life stages of a product's life cycle (Suh and Huppes, 2005). In an integrated hybrid model both the process based-model and the input-output based model are merged into one matrix (Suh, 2004; Heijungs *et al*., 2006). This framework allows full interaction between individual processes and industries for all stages of the product life cycle. However, this method is more complicated and more time and labour intensive.

3.1.2.2 Economic Methods

There are various techniques for economic evaluations of policies, projects plans and products. Some of these are also widely used in environmental economics. These include Life Cycle Costing (LCC), Cost Benefit Analysis (CBA), Total Cost of Assessment (TCA) and ExternE. LCC and CBA are used to calculate general costs including environmental, while TCA and ExternE are specifically concerned with the assessment of environmental and health costs and energy costs, respectively. Sometimes it is argued that economic methods like CBA and TCA are already integrated methods accounting at least for the economic and environmental dimension of sustainability. Others argue that monetary accounting of environmental impacts is not integrated, because methods for translating ecological facts into monetary terms is limited and contested (Neumayer 1999). Due to this ongoing argument these economic methods are not included in section 3.1.2.3 under integrated methods.

(i) Life Cycle Costing (LCC):

LCC calculates the total costs of a product, process or activity discounted over its entire life span (Ness *et al*., 2007). In principle, LCC is not associated with environmental costs, but costs in general. Traditionally, LCC is used for an investment calculation to rank different investment alternatives to help decide on the best alternative.

LCC has recently emerged as a likely concept and tool for the evaluation of the second dimension of sustainability, i.e. economic aspects associated with a product's life cycle (Rebitzer and Seuring, 2003). In combination with LCA, it enhances the application of life-cycle approaches for decision making. The use of common data and models and many synergies between both approaches (LCA and LCC) offer additional advantages of the combined use of LCC and LCA. The comparable structure of the two methods also provides the possibility to combine their results in terms of eco-efficiency measure (i.e. costs per unit of environmental improvement or environmental improvement per unit of cost) (Udo de Haes *et al*., 2004).

(ii) Cost Benefit Analysis (CBA):

CBA is a well-established analytical method for assessing the total costs and benefits from a planned project. In principle, all costs and benefits, including environmental and social costs, should be included and monetised. In the evaluation the costs are compared to the benefits.

In the context of sustainability assessment, CBA could be an effective method for weighing the social costs and benefits of different alternatives. CBA can be similar to an LCC when applied on products, although LCC typically does not include benefits (Finnveden and Moberg, 2005). Measuring expected benefits, or placing monetary value on the benefits in a simplistic way is often problematic with CBA (Ness *et al*., 2007).

LCA provides essential inputs into CBA for environmental impacts, but due to the different conventions of measurement the "marriage" between CBA and LCA is complex (OECD, 2006). Contrary to LCA and other methods for environmental decision support, CBA can take the time horizon of effects into account by discounting future costs and benefits (Wrisberg *et al*., 2002). A variant of CBA is Cost-Effectiveness Analysis (CEA). In CEA, the focus is on finding the best alternative activity, process, or intervention that minimises the costs of achieving a desired result.

(iii) Total Cost Assessment (TCA):

The TCA methodology is based on a life cycle approach, taking a wider view of potential environmental and health risks and costs (CWRT, 2000). Since TCA is a support method for making informed decisions regarding environmental and health improvements, having a detailed understanding of the pollutants generated and the human health exposure effects for a product or process is essential. The outputs from LCI can serve as inputs for the TCA methodology, where they are translated in to an economic value.

(iv) ExternE:

Since 1991 the European Commission has supported the development and application of a framework for assessing external costs of energy under the ExternE (Externalities of Energy) project series. The ExternE methodology uses LCA in combination with impact pathway analysis (IPA) and CBA to get a complete assessment of external costs due to electricity production, including impacts that occur upstream and downstream of the power plant itself (ExternE, 2005). The ExternE methodology provides a framework for transforming impacts that are expressed in different units into a common unit – monetary values. Monetisation is based on the concept of willingness to pay (one of the approaches used in CBA), which seeks to reflect society's views on value. By doing so it provides the assessment which is beyond the normalisation of environmental burdens in LCA. Moreover, it takes into account the specificity of burdens (e.g. air pollutants) with respect to the location in which they are released. The methodology has been used to inform policy makers in air quality policy, waste policy and energy policy.

(v) Eco-Efficiency Analysis (EEA):

Eco-efficiency analysis is a business management method. Though eco-efficiency is popular in many circles as a concept, eco-efficiency considerations in daily practice are sporadic (Huppes and Ishikawa, 2005). Empirically, it refers to a ratio between an environmental impact and economic cost or value. Thus EEA adds economic analysis to LCA or simplified LCA. It highly aggregates both the results of the environmental investigation and the economic analysis. Although the environmental assessment is based on LCA, the aggregation of the results is not in line with the ISO LCA methodology.

(vi) Partial Equilibrium Models:

A partial equilibrium model is an economic equilibrium model of the market of a specific good or a few selected goods. It is based on the assumption that changes in this market do not affect the price, supply and demand of other goods. The theory of supply and demand is an example of partial equilibrium analysis. In a traditional LCA model, the unit processes are directly connected by physical flows. By introducing partial economic models, the LCA model accounts for the fact that these physical flows are traded on a market (Ekvall, 2000). This makes it possible to quantify, for example, several types of rebound effects. An increase in the use of a good in the life cycle typically can contribute to increasing the market price of this good. This not only stimulates the production of the good, but also reduces the use of the good in other life cycles (Ekvall and Weidema, 2004). Partial equilibrium modelling describes both of these effects through the concept of own-price elasticity of demand and supply.

3.1.2.3 Integrated Methods

(i) Multi-Criteria Decision Analysis (MCDA):

MCDA methods support comparison of, for example, different policy options, on the basis of a set of criteria (DTLR, 2001). Such criteria may or may not be measured in monetary terms as done in CBA. Consideration of multiple criteria is particularly applicable to cases where a single-criterion approach (such as cost-benefit analysis) falls short, especially where significant environmental and social impacts cannot be assigned monetary values. Furthermore, MCDA tends to be more "transparent" than other methods such as CBA since objectives and criteria are usually clearly stated, rather than assumed (OECD, 2006).

A large number of multi-criteria evaluation methods have been developed and applied for different policy purposes in different contexts. In the simplest of MCDAs, the final outcome is a weighted average of the scores, with the option providing the highest weighted score being the one that is "best". More sophisticated techniques might be used for more complex decisions (DTLR, 2001). The selection of an appropriate method for MCDA depends on the decision rule preferred (compensatory, partial-compensatory and non-compensatory) and the type of data available (quantitative, qualitative or mixed) (Azapagic and Perdan, 2005a&b).

MCDA can be effective in supporting the assessment of and decision making on complex sustainability issues because they can integrate a diversity of criteria in a multi-dimensional guise and they can be adapted to a large variety of contexts (de Ridder *et al.*, 2006). By incorporating both qualitative and quantitative data and by counting monetary and non-monetary aspects, MCDA allows decision makers to include a full range of economic, environmental, social and technical criteria (Ness *et al.*, 2007). In relation to LCA, MCDA can be used for interpretation of the obtained results (see Figure 3), which come in different units of measurements and often show goal conflicts (Geldermann and Rentz, 2005).

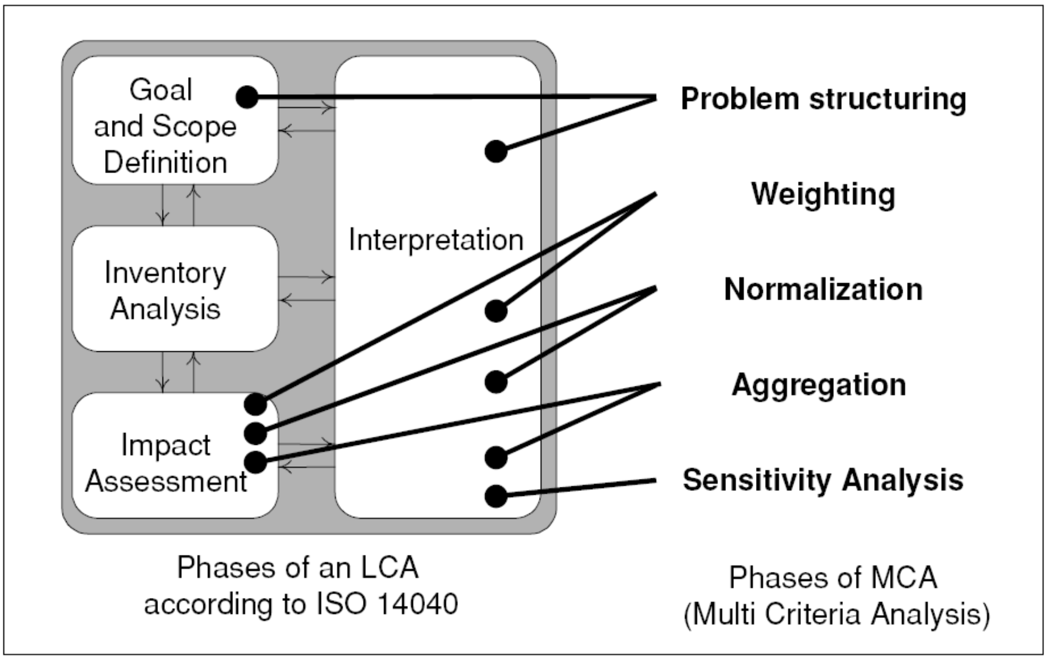

Figure 3: Application of MCDA in LCA (Source: Geldermann and Rentz, 2005)

Therefore, this review shows that a number of different frameworks and methods exist that are either related or could be LCA-related. The next section examines how these frameworks and methods might be used for broadening and deepening LCA.

4 Options for Broadening and Deepening

The options for broadening and deepening of LCA raise a number of key questions about the integration of sustainability concerns in society, including:

- How are life cycle systems connected to broader environmental, economic and social mechanisms and values?
- How do specific product and technology choices influence societal development at the macro-level?
- How can dynamics in society, which could influence the investigated products and technologies, be modelled?
- How to consider dynamic effects through increased use of certain product alternatives (which may prove favourable in a static LCA study), e.g. through cumulative impacts of non-renewable mineral use or expanded use of biomass and the subsequent enlargement of cropping area?
- How to assess the interregional specification of product chains, i.e. the circumstance under which the life-cycle impacts affect regions differently? Regions may vary with regard to vulnerability or susceptibility for impacts and often decisions are taken in manufacturing countries - based on ISO LCA - which focus on nearby effects with the consequence that impacts tend to be shifted towards other regions, often in developing and transition countries.
- How to target policy interactions: what material- and/or product-specific decisions have to be made to contribute to an overall reduction of environmental impacts and an improvement of socio-economic performance? What is the appropriate level of policy intervention (product, firm and nation) considering substitution and growth effects as well as limited knowledge and uncertainties about life-cycle impacts?

In order to address these questions, broadening and deepening of LCA needs to be able to link the analysis of a “product system” (ISO 14040, p.2) at different levels of governance. This notion is also supported by evidence of the CALCAS Work Packages on governance requirements and user needs (WP4, WP6).

Governance at the micro-level is related individual companies and households. On the firm level this could be achieved by connecting LCA product systems analysis to Corporate Social Responsibility reporting, to product development and design (e.g. by eco-design methods) or to cost accounting (e.g. by total cost accounting).

The next governance level would be the meso-level e.g. sectors such as the automotive, the agricultural or private sector. For example, it can describe the level which is statistically represented by the nomenclature of economic activities (Nomenclature générale des activités économiques, NACE) which lists economic activities for statistical purposes. The NACE classification forms the basis of the EU 6th

Framework programme EXIOPOL-project, which are aimed at developing a detailed environmentally extended (EE) Input-Output (I-O) framework.

The term *meso* is also used in a broader governance context. In this context it describes specific policies which are aimed at improving conditions for the development of economic activities (e.g. regional policy, technology policy, industry policy). It also covers the network of institutions and organisations which support companies (e.g. chambers of commerce, associations, and research and training institutions).

The highest governance level would be at the macro-level – e.g. the world, world regions (e.g. the EU) or national economies.

As outlined in section 2.3.4 of the CALCAS Deliverable 1, the link of the product system LCAs to higher levels of analysis and governance could be achieved by at least three approaches for broadening and deepening LCA:

- deepening and broadening of the standardised LCA;
- linking LCA to economic modelling with physical extensions; and
- linking LCA to physical modelling of economic activities.

Deepening and broadening of the standardised LCA is explored in WP5 and is therefore not further discussed in this position paper.

An example for an economic model with physical extensions is the National Accounting Matrix including Environmental Accounts (NAMEA) which is linked to the conventional Input Output Model of the UN System of National Accounts (SNA). NAMEA is based on the United Nations Standard of integrated Environmental and Economic Accounting (SEEA). NAMEA serves as a framework for presenting the contribution of industries and households to a variety of environmental concerns (emissions to air, waste water, and waste) compared to their economic performance. Some Member States have included environmental expenditure, environment taxes, the use of natural resources (e.g. energy or water use) and land use in their NAMEA framework (Goosens *et al.*, 2007).

An example for linking LCA to a physical economy-wide model has been established by van der Voet *et al*. (2005) who developed a methodology to create an overview on the impacts connected to the flow of materials in and out of the economy. The methodology represents probably the most comprehensive LCA-based impact assessment of material flows.

The question of this paper and the subsequent SWOT analysis is whether the evolution of models separately from LCA can be used to deepen and broaden life cycle analysis. The advantage of this approach would be to take LCA beyond environmental considerations. It could also eventually lead to integrated assessments covering all dimensions of sustainability. The risk is that the LCA would be ‘stretched out’ beyond recognition or a manageable scope as well as leading to the increased human and financial resources requirements.

This might lead to the need to trade-off between broadening and deepening of LCA. Broadening assessments will ultimately result in more superficial assessments of each economic, social and environmental dimension while at the same time increasing the number of criteria that need to be considered. Simultaneous broadening and deepening seems unlikely because it would require substantial analytical know-how and significantly more time and financial resources. Current practice in Impact Assessment in the European Commission and initial analysis of WP6 indicate that time and money are among the main limiting factors to broadening and deepening analysis. Many stakeholder agree that methods are already complex and that more complexity will increase uncertainties and decrease acceptability.

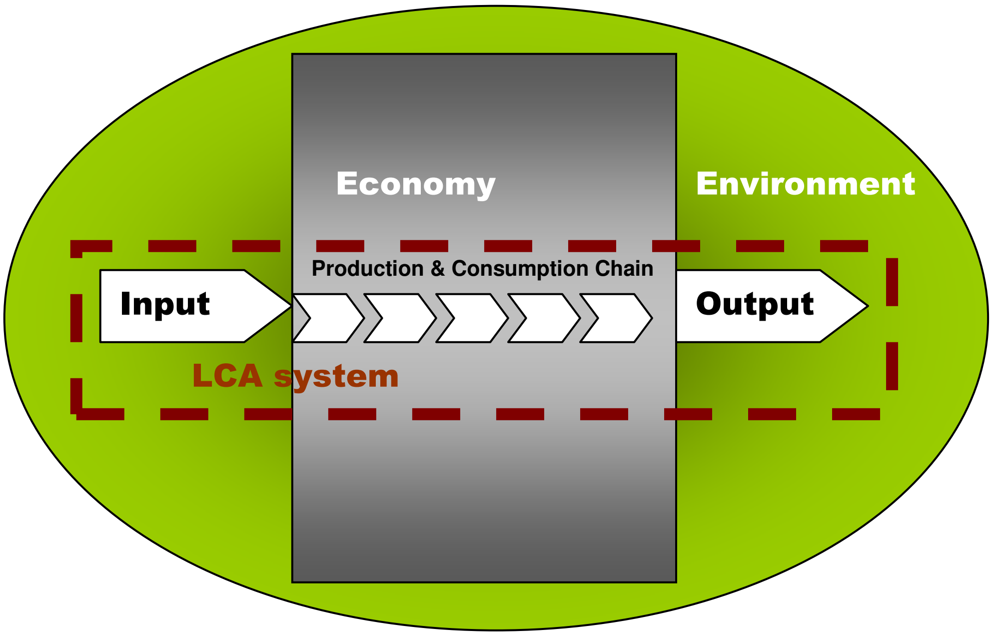

Figure 4: LCA system borders at the interface of economy and nature

The starting point for broadening and deepening LCA is the physical perspective of LCA on production and consumption with regards to inputs from and outputs to the environment. Stakeholders interviewed in the initial analysis of WP6 seem to agree that current LCA seems to be a good starting point for venturing out towards sustainability. Figure 4 shows that the LCA system borders are cross-cutting ecological and economic system borders. This requires not only modelling on environmental inputs and outputs, but inherently also requires a model of the economy (even if it is only a black box model).

Science has developed a broad supply of life cycle approaches (as discussed in Section 3). On the demand side, different policies emerge on different governance levels (Section 2) requiring these physical and economic models. Table 3 gives examples for some of the sustainable production and consumption policies and possible relations to economic and physical models.

Table 3: Examples of Governance Levels, Policies, Economic and Physical Models

Governance Level	Policies (examples)	Economic Models (examples)	Physical Models (examples)
Macro	Thematic Strategy for the sustainable use of resources; Integrated Product Policy; Thematic Strategy for prevention and recycling of waste	Computable General Equilibrium (CGE) modelling; Input Output Analysis (IOA)	Material Flow Analysis (MFA) Substance Flow Analysis (SFA) Environmental Input Output Analysis (EIOA)
Meso	Green Public Procurement; Environmental Technology Action Plan (ETAP)	Input Output Analysis (IOA)	Environmental Input Output Analysis (EIOA) Life Cycle Technology Assessment (LCTA)
Micro	Eco-Management and Audit Scheme (EMAS) Eco-design Eco-labelling	Cost Benefit Analysis (CBA)	ISO-LCA Material Input per Service Unit (MIPS)

Figure 5 shows a number of methods and models with respect to spatial and temporal dimensions. The starting point is ISO-LCA as a steady state type of analysis from cradle to grave, shown in the lower left corner of the figure. MIPS is another kind of micro 'cradle to gate' analysis with the focus on categories of resource consumption without assessing impacts. Next to this LCA 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, which allows linking the micro performance to meso and macro levels.

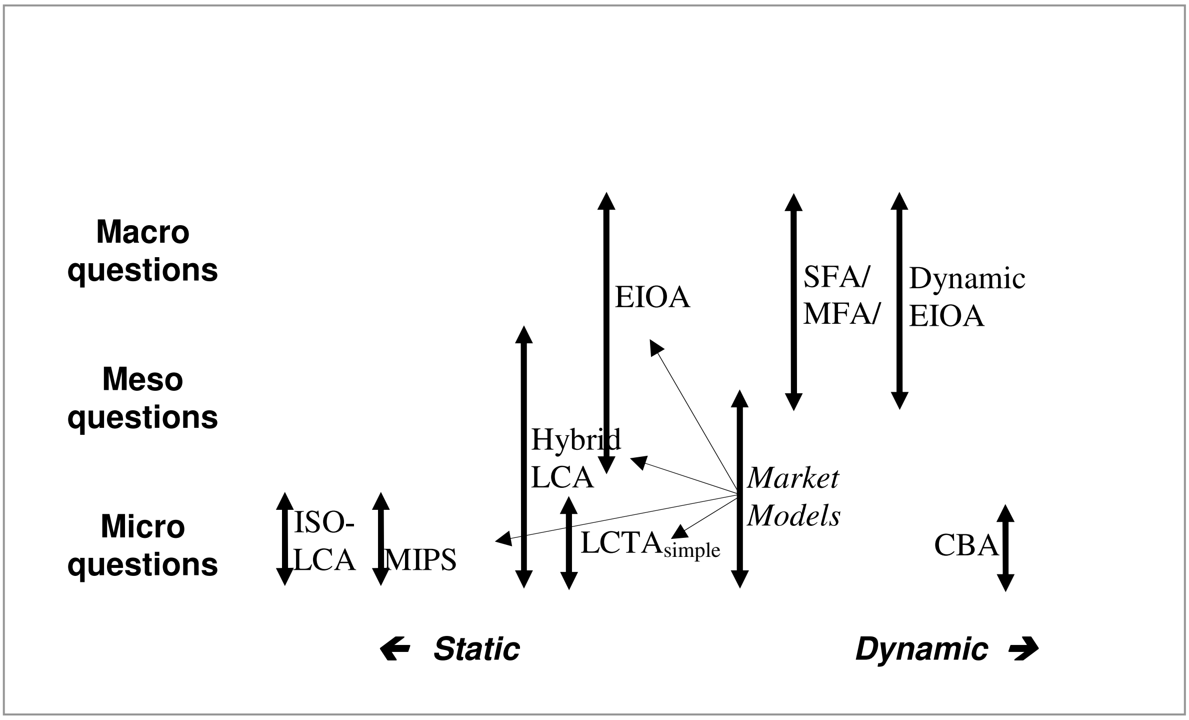

Figure 5: Broadening and deepening LCA: Possible tools and methods

Next to the environmental part of life cycle analysis, economic and social aspects can be incorporated in the same scientific framework, thus broadening LCA. The link to EIOA seems quite relevant here as well, as many social aspects can more easily be framed in an IOA, e.g. income distribution or the value added per working hour.

More fundamental deepening of life cycle analysis involves the integration of more aspects than currently used. Modelling could support this integration. Partial and non-life cycle models like market models, for example, could indicate relevant economic aspects.

Central for integration of different aspects is to make the model time specific. This is also important for inter-generational burden shifting. At a micro level, the simplest time-specific model is Cost Benefit Analysis (CBA). As outlined in the CALCAS D1, it seems 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 also possible with similar difficulties as in adding economic and social aspects to environmental LCA. Making the models time-specific does not yet imply that mechanisms would be integrated; they may be used independently from CBA. The CBA model, with environmental aspects added as in environmental LCA, has a number of advantages compared to steady state LCA for sustainability analysis. Specifically, by allowing discounting, the analysis is closer to economic analysis of investment options. Nevertheless, it is questionable whether economic discounting applies to biophysical impacts.

There are methods that already provide integration mechanism, as in dynamic EIOA. Principles for integrating different approaches have also been explored in the EU Framework Programme 6 projects Sustainability A-Test (Table 4) and MATISSE, which has evaluated a number of integrated models (Table 2). These models take into account market mechanisms, income effects, investment functions, etc, and in that sense are more realistic than steady state LCA models. However, the interpretation of steady state LCA models is much more straightforward. Furthermore, more aggregate models cannot specify products, technologies and only to a certain degree specific sectors and markets.

4.1 Broadening LCA

Broadening LCA towards social, cultural and economic aspects would move LCA from environmental towards sustainability assessments. A (limited) need for this has been indicated through stakeholder interviews in WP6. This would be an opportunity to increase the significance of LCA in political spheres beyond environmental policy, e.g. towards social and economic policies. Integrated sustainability assessments could be the basis for identifying synergies, win-win options and trade-offs between the different dimensions of sustainability. However, broadening LCA also bears risks as it would introduce an even larger number of criteria to consider. By definition, the choice of criteria will be subjective thus making LCA more vulnerable to interest-guided controversy.

A number of FP6 research projects (e.g. Sustainability A-Test, MATISSE and FORESCENE) identify participatory solutions as answer to the selection dilemma of the scoping and framing (see section 3.1). Improved consideration and integration of participatory approaches has also been highlighted at several stages of the CALCAS research e.g. at the CALCAS digression meeting in June 2007. Deliverable 6, for example, states: "*Participation techniques and their link with LCA-tools are not very well developed. LCA-tools are perceived largely as a technical effort, while the social framing of problems, the set up of studies and the use of the result is largely ignored. The link of LCA tools with participatory techniques may overcome this weakness.*" (D6 draft 1, p. 16). In this context institutionalisation of reflexivity is proposed and deliberations as an element for providing the appropriate framework conditions for discursive practices legitimating results (see draft CALCAS Deliverable 6 section 3.4 Reflexivity and institutionalisation).

The scoping phase would be even a greater challenge for a broadened LCA than for ISO LCA. The difficulty of the right framing of the analysis and combination of analytical methods can be illustrated by the case of assessing the impacts of an increased use of biofuels as targeted by the European Council. In the assessment of LCA options for sustainable governance (CALCAS Deliverable 6), ten different levels of analysis have been discerned, each level relating to broadening the modelling choices and empirical analysis (draft CALCAS Deliverable 6, section 3.2).

The example of EU biofuels policies had also been chosen in the Sustainability A-Test project as a test-case for applying combinations of analytical methods for impact assessment. The main conclusions of the exercise are listed in Table 4. In the integration and synthesis report it has been recommended that "*further research into tool combinations should, in particular, address tool combinations and tool usage in connections with actual policy-supporting integrated assessment processes, such as the Impact Assessment procedure used by the European Commission*" (de Ridder *et al*., 2006, p. 92).

Table 4: Conclusions from the Sustainability A-Test project (de Ridder *et al*., 2006)

Conclusion 1:	An integrated assessment for sustainable development is best supported by a *combination* of tools.
Conclusion 2:	Not too many tools should be used in an assessment, and tools do not necessarily have to be linked.
Conclusion 3:	The potential of combining tools is largely unexplored and could be significant.
Conclusion 4:	Defining the scope is crucial for the outcome of an assessment and could be supported by participatory tools.
Conclusion 5:	An integrated assessment for sustainable development combines quantitative and qualitative information. Tools are available for making this combination.
Conclusion 6:	Tool use is hampered by jargon.
Conclusion 7:	Scientists need to better explain the added value of their own tools and learn about other tools.
Conclusion 8:	Impact Assessments could benefit from the results of assessments done earlier in the policy-making process.
Conclusion 9:	Impact Assessment is not a comprehensive integrated assessment for sustainable development.

Participatory and reflexive procedures could be one approach to broaden the scope of assessment towards social aspects which remain a challenge for broadening LCA. The development of social criteria is an objective of the Task Force on Integration of social aspects into LCA in UNEP-SETAC Life Cycle Initiative (see also: http://lcinitiative.unep.fr/) and is currently still ongoing. A feasibility study has been published (Griesshammer *et al*., 2006), which has not yet specified social aspects to be covered in (broadened) LCA. In general, the link to social aspects with or without participatory and reflexive procedures is largely unexplored and requires further research.

It is obvious that a number of relevant economic and social aspects are overlapping. These socio-economic aspects include income distribution and employment levels. Other aspects depend only on social goals, including freedom of association, discrimination or forced labour. The integration of social aspects is still a difficult challenge, because they depend on a wide range of different behavioural aspects, cultural identities and worldviews. In developing countries social aspects may be of prime importance for domestic reasons, while their role in global industrial systems may be analysed from very different perspectives. A possible solution is a focus on human rights and international standards like the International Labour Organisation (ILO) conventions. Such an approach would not solve all problems as international standards are not the result of a democratic process; furthermore, there are many laws in democratic countries that do not correspond to international standards.

A particular challenge addressed in the Sustainability A-Test project is the knowledge management. The project has demonstrated that the spectrum of different methods and models that could be used in the context of sustainability is very broad and exceeds know-how capacities of most experts. It is even less likely that practitioners have the necessary knowledge to choose the most appropriate concepts, methods and tools for assessing impacts of their decision-making. Sustainability A-Test has made a first step towards knowledge management by setting up an internet-based electronic handbook[6]. For broadening assessments it is highly recommendable to develop long-term strategies for open-source knowledge management systems. Open access to information on different tools would support research and development, application of concepts, methods and models. If coupled with appropriately open-research strategies, this could eventually increase the likelihood of integration of different concepts, methods models. The links of open-source knowledge management systems to open-source databases as well as commercial software packages should also be explored.

With regards to integrated assessments, de Ridder *et al.* (2006) underline the importance of two phases of integration:

1. Problem framing and
2. Finding solutions.

These central recommendations are at the heart of two FP6 research projects MATISSE and FORESCENE, which are partly built on Sustainability A-Test (see section 3.1.1). Depending on the results of the projects, frameworks developed by projects like MATISSE and FORESCENE could be tested and further developed.

[6] www.sustainability-atest.net

4.2 Deepening LCA

The primary aspect of "deepening" the present LCA models and tools is to improve their applicability in different contexts while increasing their reliability and usability. Such improvements could be reached by indicating additional aspects in terms of:

1. spatial differentiation
2. temporal specification
3. integration of additional indicators.

1. Spatial differentiation

An important deepening aspect is the integration of environmental impacts on different system levels such as global, regional and local. Environmental impacts range from a global systems changes (e.g. global warming, ozone depletion), over regional phenomena (e.g. acidification), down to the local level (e.g. soil pollution). Today most impact categories make no distinction between different spatial categories even if the environmental impact is a regional or local one. Acidification is most of the time summed up to one category of acidification potential without taking into account the region where the acid fall-out occurs (e.g. by taking into account regionalised critical loads). An important case where spatial differentiation is needed is the case of biofuels (see also draft D6, section 3.2). Several aspects that directly influence the environmental impacts of the production of biofuels and other products from agriculture depend on the regional or local climate, soil fertility, natural vegetation and water availability. In such cases ISO-LCA may be a starting point, but results need to be placed in a broader context, indicating consequences of land-use shifts or opportunity costs.

2. Temporal differentiation

Most LCA even if they address future oriented questions do not cover time as an important aspect for changes in the investigated system, although changes over the time could be a key issue. This includes uncertain developments of technologies, like increased or decreased efficiency, new processes or constraints (Cohen, 2007) but also much more certain developments such as development of a material stock and the availability of secondary materials. These are important aspects of the environmental impacts of specific production systems.

Obviously, there is a large gap between investigations on micro and macro level (Schütz and Ritthoff, 2006). Most investigations at the macro level are time specific but most investigations on the micro level are not. Making LCA time specific can improve the connection between micro and macro levels. Furthermore, it must be taken into account that the level of technological development does not correspond directly to the level of environmental problems that should be addressed. Ideally, all micro level questions should be answered in terms of macro level effects of involved choices.

3. Integration of additional indicators

ISO-LCA addresses the most pertinent environmental problems; however, this does not necessarily mean that these indicators are adequate for all applications. For example, the biofuels case shows that consideration of additional aspects is necessary, including the knowledge on pesticides, the influence of agriculture on biodiversity or the effect of land use change on albedo, water evaporation or wind speed.

The integration of additional indicators is covered by the UNEP-SETAC Life Cycle Initiative (Table 5) and in the European Platform on Life Cycle Assessment.

Table 5: Impact categories covered in UNEP-SETAC Life Cycle Initiative

(Jolliet *et al.* (2004)

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

4.3 Criteria for Broadening and Deepening

The central purpose of broadening and deepening of LCA would be to improve decision-making processes with respect to the sustainability of human activities. Based on D1, D3 and D6 the following criteria could be applied for deciding whether broadening and deepening LCA move us closer to this objective:

- Consideration of mass and energy conservation principles:

The law of mass conservation by mass balancing of inputs and outputs in the domain of physical accounting is applied by e.g. LCA, SFA, MFA, MIPS, Energy/Exergy Analysis and Life Cycle Optimisation. Mass and energy conservation laws are either violated or not considered in most economic models.

- Development of the ecological scope of LCA:

Further development of LCA is needed in the area of other environmental impacts and indicators (e.g. land use, biodiversity, genetic pollution, erosion, indoor air quality and odour).

- Integration of or links to economic mechanisms:

Material flows which are analysed in LCA are often driven by economic exchange processes and have repercussions on economic performance. Thus, it is desirable to model these interlinkages.

- Integration of or links to social aspects:

Parts of economic consumption and production patterns are within the system boundaries of LCA. People are the actors within these patterns and subject to economic and physical transfer. Social aspects of these transfer processes would be desirable for a complete consideration of sustainability.

- Assessment of intra- and inter-generational burden-shifting:

Another feature that is essential for sustainability assessment is the detection of inter- or intra-generational burden shifting. Intra-generational burden shifting occurs if negative environmental impacts are mitigated at the expense of other social, economic or environmental assets of the current generation. Inter-generational burden-shifting happens when negative environmental impacts are compensated for at the expense of social, economic or environmental assets of future generations.

- Integration of or links to cultural aspects:

Cultural aspects are main drivers of the consumption and production patterns. Nevertheless, they usually play a minor role in LCA and other sustainability-oriented assessments.

- Integration of or links to policies and administrative mechanisms:

To be useful, LCA also needs to be linked to policy-making. To this end, LCA should serve the need of specific policies (e.g. the EuP directive) or cross-cutting administrative mechanisms such as the European Commission's Impact Assessment or corporate quality control procedures.

- Consistency between micro, meso and macro levels:

For supporting systemic analysis and multi-level governance, a compatibility of assessments with the possibility of aggregating and disaggregating data flows would be desirable. Ideally this would lead to the possibility to use LCA data relating to production systems for analysis and decision-making on higher levels of governance (e.g. firm, sector, region, country, world) and vice versa.

- Integration of reflexive and participatory methods:

To increase the use of relevant knowledge and improve the social framing of problems, the scoping of analysis and the use of results, there is a need for integration with participatory approaches. Reflexivity might also be needed for quality control of LCA.

In addition to these content-oriented criteria, the interviews in WP6 suggest the following practical criteria, which can be in conflict with the above mentioned criteria:

- More simplification:

Standard ISO-LCA is too time-consuming for everyday use. The complexity of ISO-LCA is one of the main drivers behind the creation of adapted and tailored LCA methodologies.

- More standardisation:

Standardised methods along with standards regarding data quality is requested by some stakeholders for improving comparability of results.

5 Summary and Conclusions

Life cycle thinking is increasingly permeating various sustainable development policies and is becoming a part of the way we conceptualise environmental issues and the way we deal with them. The environmental starting point for finding suitable answers to the questions emerging from the sustainability paradigm is the guiding metaphor of the life cycle approaches.

Sustainable consumption and production policies are setting the demand for life cycle thinking, particularly in Europe, where a movement promoting production and product-oriented environmental policies has evolved. In a broader context, the life cycle approach is a central theme in the Integrated Product Policy as well as in recent EU Communications related to sustainable use of resources, waste prevention, and recycling. These policies aim to reduce environmental impacts throughout the life cycle of products, with a specific focus on the impacts in general, those related to waste, and those related to resource consumption. To support sustainability decision-making, there is a need for structuring different life cycle approaches and combining with economic and social assessments.

There is a multitude of concepts, methods, models and tools that are related to LCA and this paper has provided an overview of these approaches. These tools are designed for the specific decision-making situations and address one or more sustainability dimensions. Also different methods and application frameworks use different system boundaries and different objects of the studies. For example, strategic environmental assessment (SEA) and sustainability assessment (SA) are intended for policies, plans and programmes, whereas environmental impact assessment (EIA) is used for planned projects.

Environmental accounting methods such as Material Flow Analysis (MFA), Substance Flow Analysis (SFA), and Energy/Exergy analysis (EA) focus on natural resources are methods for estimating environmental ‘pressures’. Life cycle costing (LCC) is used for economic assessment of products and services. Cost benefit analysis (CBA) takes into account environmental and social costs and benefits. However, converting these into monetary terms is controversial. On the other hand, Multi-Criteria Decision Analysis (MCDA) allows decision makers to include a full range of sustainability criteria without the need of using monetary values.

Combinations of LCA with some of these methods can be used to provide a more comprehensive picture. For instance, at a project level, Environmental Impact Assessment (EIA) can complement LCA by providing information on local, site-specific aspects and vice versa (LCA providing information on global impacts). Data generated from Risk Analysis (RA) are useful in assessing toxicity, an impact category estimated used in LCA. Similarly, Input Output Analysis (IOA) can be used to support Life Cycle Inventories (LCI). Combination of IOA with LCA, as in hybrid approaches, reduces the data collection effort and provides more complete system definition. However, the IOA and hybrid LCA are only useful at the macro-level. At the micro-level., e.g. process level, life cycle optimisation and Sustainable Process Design (SPD) make use of LCA in combination with other methods for sustainability assessment of a process or technology.

Ideally, broadening and deepening LCA should meet the following criteria:

- Consideration of mass and energy conservation principles;
- Development of the ecological scope of LCA;
- Integration of or links to economic mechanisms;
- Integration of or links to social and cultural aspects;
- Assessment of intra- and inter-generational burden-shifting;
- Integration of or links to policies and administrative mechanisms;
- Consistency between micro, meso and macro levels;
- Integration of reflexive and participatory methods;
- More simplification; and
- More standardisation.

Although these principles are theoretically not in conflict, it is unlikely that the existing pool of concepts, methods and models can be integrated in a way in which one concept, method or model emerges that meets all criteria. Therefore, integration is recommended where appropriate and possible, but also an intelligent combination and selection of concepts, methods and tools depending on the policy question.

Each concept, method and model has strengths and weaknesses, which will turn into an opportunity when policies demand analysis within their scope and become a risk when policy questions are not properly addressed. Therefore, the next step is to carefully assess strength, weaknesses, risks and opportunities for each concept, method and model in the light of the above mentioned criteria.

5.1 Selection of Methods for SWOT Analysis

Sustainability information systems require a framework for combining a multitude of different concepts, tools and methods. Therefore, the options for broadening and deepening LCA approaches should be selected according to one paramount objective:

improved decision-making towards sustainability. Thus the assessment approaches should provide intelligence for a sustainable development in a coherent and consistent way. Vertically, the methods should reach from the micro level of individual households, companies and products up to the macro level of entire economies. Horizontally, concepts, methods, models and tools should encompass at the social, economic and ecological dimensions. However, the challenge lies in combining and integrating these aspects in a conceptual relation and logical sequence. It is even more challenging to have one comprehensive method which meets the needs of diverse users. The latter is particularly difficult because different users have different needs and capacities to apply these approaches in sustainability decision making. SMEs especially find the current form of LCA too complex to use due to limited technical, financial and human resources. Others consider the ISO-LCA too restrictive and there are differences on underlying assumptions such as system boundary and allocation methods.

For selecting most promising development paths for broadening and deepening LCA, it is proposed that methods should be assessed for the following criteria:

- *Conceptual*: How does it consider the issues like intra- and inter-generational equity, burden-shifting, ecological stability, etc?
- *Operational*: What are the specific characteristics of the method which could be used for further development of LCA, for example assessment of impacts (such as land use, biodiversity, genetic pollution, erosion, indoor air quality, income level, health, jobs, inequality, etc.), availability of data, etc.?
- *Integration*: How does it link different mechanisms both horizontally and vertically (e.g. physical/economic/cultural; micro/meso/macro relations)?

However, it is not expected that all selected methods will meet all criteria, For example, a method may be chosen for SWOT analysis because it has the ability of integrating different sustainability aspects although having operational weaknesses. Another method may have the operational advantage of data availability, but lacking the ability of aggregating the information on higher levels of decision-making.

Based on the Description of Work (DoW), theoretical considerations of the scoping paper (D1) and governance aspects (D3), which have been integrated and further developed in Section 4, as well as practical considerations, it has been decided within WP3 to expand the original list of approaches in the CALCAS DoW. Table 6 provides the list of approaches which have been selected for the SWOT analysis. In addition to the 19 methods, which are listed in the CALCAS DoW, this list includes 13 additional models and methods. It is also suggested that Cumulative energy requirements analysis (CERA) can be treated as part of energy/exergy analysis (EA). The social accounting matrices (SAM) can be dealt with in connection with input-output analysis (IOA). Environmental quality function deployment (Env-QFD) or Quality Function Deployment for Environment (QFDE) are seen as part of eco-design methods (EDM). Therefore, the SWOT analysis will be carried out on 32 different methods and models as listed in Table 6.

Table 6: Methods Selected for SWOT Analysis

Methods Proposed in the CALCAS Description of Work	Additional Methods Suggested
Materials Flow Analysis (MFA)	Total Cost of Ownership (TCO)
Substance Flow Analysis (SFA)	ISO Life Cycle Assessment (LCA)
Cost-Benefit Analysis (CBA)	Externe
Life Cycle Costing (LCC)	Eco-Design Method (EDM)
Input-Output Analysis (IOA)	Multi Criteria Decision Analysis (MCDA)
Environmental Input-Output Analysis (EIOA)	Life Cycle Activity Analysis (LCAA)
Integrated Hybrid Analysis (IHA)	Partial Equilibrium Models (Applied e.g. to Energy Systems)
Material Input Per Unit of Service (MIPS)	Carbon Footprint
Cumulative Energy Requirements Analysis (CERA);	Social LCA
Social Accounting Matrices (SAM);	Strategic Environmental Assessment
Total Cost Accounting (TCA)	Sustainability Assessment
Risk Analysis (RA/ERA/HERA)	Life Cycle Optimisation
Environmental Impact Assessment (EIA)	Sustainable Process Design
Eco-Efficiency Analysis (EEA)	
Eco-Design Methods (EDM)	
Product Oriented Environmental Management System (POEMS)	
Environmental Quality Function Deployment (Env-QFD)	
Energy/Exergy Analysis (EA)	
Computable General Equilibrium Models (CGEM)	

5.2 Recommendations for SWOT Analysis

To identify the potential of various methods in enhancing LCA and its applications, it thus makes sense to raise the questions:

- Which methods adequately elaborate social, economic and ecological aspects?
- What are the key assumptions and limitations in each method?
- How different methods address other aspects, such as spatial (site dependent), temporal (retrospective/prospective), handling time (steady/dynamic state), etc?
- Will they be helpful in simplifying the practical application of LCA without compromising the accuracy?
- Are there any issues regarding data availability and accessibility for a particular method?

To answer these and other related questions, a detailed SWOT analysis will be carried out on the relevant methods (Table 6) to assess their potential and limitations in broadening and deepening the LCA.

SWOT analysis is a handy and flexible tool which should explain not only strengths and weakness of individual methods, but also risks and opportunities in relation to sustainability policies. The combination of strengths, weaknesses, opportunities and threats offers all necessary components for understanding and decision-making. The information generated and sorted in a SWOT analysis is relative; therefore it can only be assessed in a comparison, as it is planned in WP3. For a targeted strategic use, a SWOT analysis needs to be orientated to an objective, which in this case is the broadening and deepening LCA for a better assessment of sustainability impacts.

In essence, it should evaluate both internal and external factors. The internal factors may be viewed as strengths or weaknesses of the methods depending upon their usefulness for assessing the sustainability of a life cycle. These include robustness, validity and reliability, application, user friendliness, intelligibility of concept, data needs and costs. The external factors may include opportunities and threats presented by the external environment (e.g. macro-economic factors, technological change, legislation and policies, political importance given to the concept or tool and socio-cultural changes, as well as changes in the research landscape). For the purposes of broadening and deepening LCA, correct identification of internal and external factors is essential, because subsequent steps in developing a research roadmap towards broadening and deepening LCA are to be derived from the SWOTs.

Table 7 provides the template for the SWOT analysis. For the subsequent steps in developing a research roadmap towards broadening and deepening LCA, a SWOT analysis of a particular method needs to answer the following questions:

- What are the specific strong points/attributes of the method that are helpful to broadening and deepening LCA and how to take advantages of those?
- What are the specific weak points / attributes of the method that might hinder broadening and deepening of LCA and how to overcome those and how to exploit them?
- What are the opportunities due to *external* conditions that are helpful to use this method for broadening and deepening LCA and how to exploit them?
- What are the threats due to *external* conditions that that might prevent using this method for broadening and deepening of LCA and how to minimise them?

The SWOT analyses will be carried out following this template in the next phase of WP3.

Table 7: CALCAS SWOT Analysis framework

Basic information: [1 page]

- Name:
- Acronym:
- Author of SWOT evaluation (name, organisation, address, e-mail):
- Level of analysis:
  micro (e.g. household, company, product level),
  meso (e.g. sectors, material flow systems, branches),
  macro (e.g. countries, economies).
- Assessed aspects of sustainability: environmental, social, economic other …
- Main purpose of the assessment:
- Description of the methodology:

Detailed description [1-3 pages]

Strength: [1 page]

a) scope of assessment (what is being assessed)
b) methodology (robustness, validity & reliability)

Weaknesses/Limitations: [1 page]

a) scope of assessment
b) methodology

Opportunities for broadening and deepening life cycle approaches: [1 page]

Benefits for social or economic development, scientific progress, primarily in relation to policies as described in section 2

Threats for broadening and deepening life cycle approaches: [1 page]

Risks caused by or for social or economic development, scientific progress, polices as described in section 2

Literature/Internet links:

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