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D15 – A SCIENTIFIC FRAMEWORK FOR LCA

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A scientific framework for LCA

Deliverable (D15) of work package 2 (WP2) CALCAS project

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SUMMARY

This document proposes a framework for New-LCA, as opposed to the established framework for ISO-LCA. Reasons for doing so are highlighted, but are evident when one looks ony superficially at the scientific literature on LCA of the last decade, covering subjects such as dynamic LCA, spatially differentiated LCA, the use of multicriteria techniques in LCA, the extension of LCA to social LCA and life cycle costing, the incorporation of rebound effects into LCA, and the use of LCA in combination with socio-economic scenarios.

After a discussion of the two central concepts, life cycle analysis and sustainability, the road is paved to focus on the model set-up for New-LCA, a modification of the original LCA that is broader in the sense of covering more aspects than environmental ones alone, that is deeper in the sense of being more accurate ad more sophisticated, and that is better founded in established disciplines, such as economics, decision theory, and thermodynamics.

It is concluded that New-LCA is an integrative activity that uses empirical knowledge from a large number of disciplines (technology, physics, environmental science, economics, political science, etc.) along with normative positions on the priorities of society and the ideological assumptions that underlie our opinions. The main architecture of a framework for New-LCA is supposed to be developed in future in such a way that the essential elements can be turned on and off in a goal and scope dependent way.

CONTENTS

1 INTRODUCTION

This chapter presents an outline of the purpose of this report, and presents briefly its context, the EU-FP6 CALCAS project. Finally it presents the structure of the report.

1.1 Background

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

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

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

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

1.2 The CALCAS project

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

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

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

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

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

These tasks have partly been accomplished within the CALCAS project, as new practical strategies in LCA. For the other part, tasks will be formulated as research lines and as a road map, in terms of a number of research lines and a number of exemplary research programmes for sustainability decision support. The strategy and road map developed is input in public and private research programmes, in academic curricula, and in R&D programmes in industry. The CALCAS deliverable D20 will describe this latter line.

The report at hand here is deliverable D15 of work package 2 (WP2) of the CALCAS project. In D15 – called the final scientific framework paper – the framework for (new) LCA is outlined.

1.3 Structure of the report

CALCAS is the acronym of a project with the full title "Co-ordination Action for innovation in Life-Cycle Analysis for Sustainability". In order to position the project – and hence the scientific framework described in the present document – we need to address the two central concepts in CALCAS:

- life-cycle analyis;
- sustainability.

In Chapter 2 we will start with the latter, while life cycle analysis will be discussed in Chapter 3. Chapter 3 then discusses ISO-LCA and its foundations and main features, whereas Chapter 5 presents an outline of the foundations and features of New-LCA. Chapter 6 presents the new LCA framework in some more detail. Chapter 7 reviews the research efforts that are needed to develop the new framework.

2 THE FIRST ELEMENT: SUSTAINABILITY

This chapter reviews the definition and interpretation of the sustainability concept. It introduces sustainability, sustainable development, and the three dimensions that are usually distinguished in the context of sustainability.

2.1 Sustainability and sustainable development

It is generally acknowledged that the term "sustainable development" (SD in short) was introduced in the report of the World Commission on Environment and Development that appeared as *Our Common Future* in 1987 (World Commission on Environment and Development, 1987). Since then, sustainable development is invariably defined as "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs". SD has been adopted as a policy principle by the UN, the EU, many countries, but it has also become a central notion for many companies, business councils, political parties, NGOs, etc.[1]

Strongly connected to SD – and often confused with it – is another term: sustainability. A thing is sustainable when it can be maintained in a specific state for an indefinite (or very long) time. Hence, sustainability is the property of a thing being sustainable. The thing can be anything: a policy, a situation, a product, a process, a technology. Hacking & Guthrie (2008, p.73) report that "At an international workshop on 'SEA and Sustainability Appraisal' it was apparent that there is little consensus regarding the meaning of Sustainability Assessment."

The fact that SD and sustainability have been embraced does not mean that these concepts are clear. In fact, they are far from clear. A lesson from analytical philosophy is that we may solve some of the conceptual problems by analysing the words and terms from a linguistic point of view. This will not solve everything, however. Sometimes we just have to accept that a term is not particularly appropriate, but that a practice has grown to use it to denote something.

Clearly, when we say of a thing that it is sustainable, we should also provide information on the state that is to be maintained. A car with a very long life time may be said to be sustainable, without paying regard to the consequences for the environment. In a wider view, it is not sustainable. Stand-alone use of the word sustainable is thus to be discommended. Likewise, the term sustainability can only refer to a thing with a specified state. Speaking of the sustainability of a product or technology has no meaning without information on the state that is assumed to be sustained. In many cases, this state is implicitly an ecological or environmental condition. People often speak of a "sustainable tourism" when they refer to tourism that has no adverse consequences for nature.

Likewise, most corporate sustainability reports have a clear focus on environmental issues: chemicals use, waste, energy[2]. They provide an accounting of the environmental pressure of the company's activities, and hardly bring in the question what is to be sustained. Again, some environmental condition is implicitly assumed, and often the social aspect is added to that. On the other hand, there are examples where sustainability does not include the environment, but merely competitiveness, hence the sustainability of business (http://www.businessnz.org.nz/file/888/7%20Pillars%20-%20Sustainability.pdf).

[1] Google reports an incredible 14,500,000 hits for "sustainable development" on January 31, 2008.

[2] Haapio & Viitaniemi (2008, p.480) write in a review of tools for the building sector: "In addition to the environmental aspect, sustainable building includes the economic and social aspects. A vision of transforming the existing building environmental assessment tools into sustainability assessment tools seems, at the moment, far away."

Sustainability and SD represent an area that abounds in terms, ranging from sustainable consumption to eco-efficiency, and from factor X to supply chain management. See Glavič & Lukman (2007) for a recent review.

2.2 The three dimensions of sustainability

The definition of SD establishes clear links with many issues of concern: poverty, equity, environmental quality, safety, population control, and so on. In general, the field of SD is subdivided into three areas: economic, environmental, and social[3]. These so-called pillars or dimensions of sustainability need to be addressed in assessing the sustainability of a project, policy, etc. Thus, the narrow interpretation in which sustainability and SD is restricted to the ecological pillar alone, is replaced by the wider interpretation where all three pillars are covered.

A popular way of expressing the three pillars of SD is known as *People, Planet, Profit* (or PPP or P3), where People represents the social pillar, Planet the environmental pillar, and Profit the economic pillar. At the World Summit on Sustainable Development in Johannesburg, 2002, this was modified into *People, Planet, Prosperity*, where the change of Profit into Prosperity is supposed to reflect the fact that the economic dimension covers more than company profit. Other well-known terms are the *Triple Bottom Line* (TBL) and the UN's *Global Compact*.

Another aspect of the popularity of SD is its visual representation. The idea of three pillars is often illustrated as in Figure 2.1.

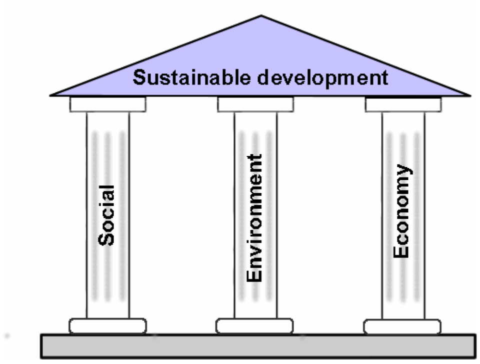

Figure 2.1: A popular way of representing SD (taken from http://www.sustainability-ed.org/pages/what3-1.htm). The metaphor expressed is that the three pillars have to be equally well developed in order to sustain the building.

Others depict sustainability in the forms of intersecting circles (as a Venn diagram); see Figure 2.2 and Lozano (2008).

[3] In literature and on the internet, many other subdivisions can be found, e.g., including a fourth pillar (culture; see http://www.creativecity.ca/news/special-edition-3/culture-fourth-pillar.html), five alternative pillars (safety, occupational health, HIV/AIDS, environment, and social investment; see http://www.arm.co.za/cr/sd_pillars.asp), or even eight pillars (sustainability, environmental performance, safety, communication, community and customer support, minimisation of waste, environmental alliances, innovation, and economic viability; see http://www.veoliaes.com.au/community-and-environment/sustainable-environmental-solutions/).

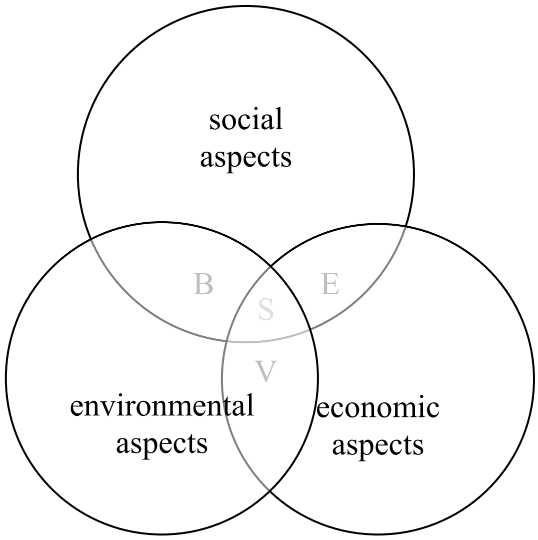

Figure 2.2: Another popular way of representing SD, as three intersecting circles. The areas of intersection represent different combinations: B for bearable, E for equitable, V for viable, and S for sustainable.

Of course, such visual representations have a merely iconic value, and do not allow to draw conclusions as such.

2.3 Sustainability analysis, sustainability indicators and decision-support

From the above, it is clear that the sustainability of a thing (project, technology, policy, etc.) is of definite interest. Policy principles and corporate accountability require that a "sustainability analysis" (SA for short) may be part of the justification to adopt a policy, to implement a technology, to purchase a product, etc. So-called sustainability indicators (SI) are an important ingredient in the process of communication, bench-marking and decision-making. Numerous schemes of such indicators have been developed, by the UN, the OECD and the EU, as well as by companies and NGOs, often subdivided into groups covering the economic, environmental, and social dimension. For instance, the United Nations Commission on Sustainable Development has developed a list of 134 SI, divided over 14 themes:

- poverty;
- governance;
- health;
- education;
- demographics;
- natural hazards;
- atmosphere;
- land;
- oceans, seas and coasts;
- freshwater;
- biodiversity;
- economic development;
- global economic partnership;
- consumption and production patterns.

Similarly, the EU (2007) distinguishes 10 themes:

- socioeconomic development;
- sustainable consumption and production;

- social inclusion;
- demographic changes;
- public health;
- climate change and energy;
- sustainable transport;
- natural resources;
- global partnership;
- good governance.

with SIs for each theme at three different levels.

Clearly, with the growing importance of SI for supporting or justifying decisions on technologies, policies, subsidies, etc. the scientific validity of such indicators is becoming a crucial factor. Any company can claim that its products are sustainable, and any NGO can deny this, but only scientifically based analysis and methods can provide a rational basis for decisions and arguments. Thus we see a need to embed the indicators for SD, and the methods with which they can be computed into the realm of scientific analysis.

Terms like sustainability analysis and sustainability indicators naturally occur in many contexts: for countries, policies, products, companies, etc. In the remainder of this report, we will focus on SA and SI in a life-cycle perspective; see also Section 3.2.

2.4 Questions for sustainability analysis

So far, we have been discussing sustainability as a "thing in itself", as something that is just there to be measured and to be analysed. As such, sustainability analysis is a so-called positive science: it describes the state of affairs, just like astronomy describes the structure of galaxies. This can be contrasted with normative[4] sciences, which are action-oriented. Medical sciences and engineering are obvious examples of such sciences.

Most sciences combine positive and normative elements. Geology describes the formation and structure of the earth, but also develops methods to detect and explore mineral resources. Economists describe the mechanisms of the labour market and unemployment, but also develop methods to stimulate the economy. This is also true for sustainability science. Although it can be pursued as a positive, descriptive activity, it contains in most cases normative, action-oriented elements, and it is in fact in most cases driven by such normative elements. The development of high-efficiency photovoltaic cells is not an accidental offspring of a fundamental science, but the result of a purposeful quest that accidentally involved some fundamental aspects as well.

The basic question we will face in this section is: what are the questions for sustainability analysis?

Man can ask many questions. At the outset, we will restrict the discussion to questions that are relevant in the context of sustainability. This still leaves open a wide range of questions. It is the purpose of this section to bring some structure in this large field.

Questions can be posed for the sake of curiosity or for the sake of making a decision. The question "How many prime numbers are there between 100 and 200?" clearly falls in the first category, and the question "What time is the next train to Berlin?" typically falls in the second category. Thus, the distinction between fundamental and applied science shows up. However, things are not always so

[4] Note that a positive science may contain normative elements. A pathologist may speak of "disease", even without having the intention to act, i.e. to cure the disease. See also Section 2.5.

easy. The distribution of prime numbers turns out to be important for cryptography and is therefore important in applications for encrypting messages, e.g. in secure internet connections. And some persons are interested in train departure times per se, without wishing to catch these trains.

Sustainability, then, sets the context of human action. As such, its questions are related to supporting decision (see above) and can be labeled as belonging to the domain of applied science. But we can delineate the realm of sustainability science even more: it is forward-looking, future-oriented. It tries to predict what will happen if a certain choice is made, what may happen if no action is taken, how certain present problems may be solved in future by choosing a certain strategy, and so on. It is not descriptive or explanatory like most aspects of paleontology, psychology and linguistics. Rather, sustainability science is more an “engineering” type of science, like mechanical engineering, medical science and pedagogic science.

Although sustainability science is not fundamental at the outset, and does not focus on descriptions or explanations per se, it may use explanations to understand the cause of problems, and to alleviate them. Thus, knowledge of the thermodynamics of industrial processes may give a clue to improving these processes, knowledge of consumer psychology may suggest ways to change preferences and behaviour, and knowledge of economic market mechanisms may be helpful in stimulating eco-innovation. Even though we have said that sustainability questions are forward-looking, looking at and learning from the past is often a way to understand the social, economic and environmental cause-effect relationships and interlinkages. A study of the unsustainability of the Roman empire or the civilization at Easter Island is thus not a purely academic affair, as we may draw lessons from it for our future actions. Moreover, back-casting is one of the possible applications of sustainability science.

Questions in the field of SA may be categorized along different dimensions:

- breadth: some questions have a narrow focus (e.g., the only consider the CO_2 emissions of technologies), whereas other questions address a broad range of effects (e.g., climate, toxics, resources, health, poverty, equity, democracy and gender issues);
- depth: for some questions shallow answers (e.g., CO_2 emissions as a pars-pro-toto for the overall environmental performance) may suffice, whereas other questions require a sophisticated analysis of changes in ecosystem composition and economic structure;
- level: questions can be posed from the micro level (e.g., on the choice between a paper bag and a plastic bag), whereas other questions address macro issues (e.g., how to reconstruct a society without fossil fuels).

In principle all these dimensions may be studied from a life cycle perspective; see the next section.

2.5 Sustainability and the role of science

The above suggests that a scientific analysis can answer questions as to the sustainability of projects, technologies, etc. It is appropriate to emphasize that this suggestion is not completely true. There are several reasons for this:

- an answer to questions on sustainability requires normative elements, such as trade-offs between economy and environment and aspects of intergenerational equity;
- a sustainability analysis involves self-denying prophecies, e.g. in predicting undesired consequences which will be combated before they have the chance to develop;
- even the aspects that are factually true are in many cases badly known to the scientists, because they involve complex and novel phenomena.

Altogether, we conclude that a scientifically based sustainability analysis necessarily involves value judgments, assumptions, scenarios and uncertainties. Following the logic of Funtowicz & Ravetz

(1990), it is our task not so much to decrease the non-factual content of an SA, nor to hide it, but to explicitly incorporate it by adding elements such as uncertainty analyses and discursive procedures.

3 THE SECOND ELEMENT: LIFE CYCLE ANALYSIS

In the previous two chapters, we sometimes used terms like life cycle or LCA without giving a precise description of what we mean. In the context of the CALCAS project, where the middle two letters stand for Life Cycle, such a demarcation of subject is highly relevant. This chapter will provide such a discussion.

3.1 Questions that require a life cycle perspective

Many of the issues in the field of sustainability have causes or consequences that extend beyond the here-and-now of the original question and the decision-maker. A choice between a plastic and a paper bag influences material suppliers upstream and waste managers downstream. And as sustainability is defined as a global concept that covers moreover present and future generations, sustainability analysis inevitably calls for a system-wide analysis. Every decision, private or collective, on the micro or the macro level, for now or the future, affects others, now and in the future, here and other places. Following this logic, it is natural to apply a life cycle perspective.

Even though almost all questions that deal with sustainability require a system-wide view, there may be good reasons to refrain from adopting a life cycle perspective in certain cases. For instance, when a producer can choose between two places to build a certain facility, and the transport distances with the rest of the supply chain are comparable, an environmental impact assessment (EIA) may provide more accurate and faster answers than a full systems analysis.

In the following sections, we will expand on those questions that require a life cycle perspective.

3.2 Definitions of LCA and related terms

Like sustainability and sustainable development, the terms life cycle and LCA have been used in a variety of ways. And just as there is the official WCED-definition of SD, there is an official and often-quoted ISO-definition of LCA: LCA is the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 14040, p.2).

It is interesting that the European Platform on LCA has provided a slightly different definition: LCA is "*a process* of compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (http://lca.jrc.ec.europa.eu/lcainfohub/glossary.vm, our italics). Thereby, it stresses that the term LCA refers to the activity ("doing an analysis") rather than to the result of that activity.

Furthermore, LCA can refer to a field of science as well as to a particular case study. In the latter case, the term "LCA-study" is sometimes used. This will be discussed further in Section 4.2.

A term like life cycle has a rich history. The life cycle concept shows up in many disciplines and topics. Organisms have a life cycle, from birth to death.[5] Businesses have one, and so do policies

[5] The term cycle itself is already noteworthy. A cycle suggests a closed path, where the begin and the end coincide, like in a roller coaster, in contrast to a trip by train from A to B. For instance, engineers study the Carnot cycle, and economists a business cycle. But from cradle to grave is not a cycle, unless the closed-system ideal of from "cradle to cradle" (McDonough & Braungart, 2002) is attained. However, when we read that a pianist or conductor is doing a "Beethoven cycle", cycle just refers to the complete work, not to end at the point of departure.

and technologies. Even products have life cycles in several meanings: from the design point of view, starting with idea generation and ending with commercialization, from the entrepreneurial perspective starting with market crystallization and ending with market termination, as seen from the cost, starting with R&D-costs and ending with disposal cost, and so on. ISO 14040 defines the life cycle as the "consecutive and interlinked stages of a product system, from raw material acquisition or generation of natural resources to the final disposal" (p.1). Even though this definition shifts the problem in part to the problem of defining a "product system", it elucidates the intention by adding the life cycle stages: raw material acquisition, product manufacture, product use, disposal, etc.

There is a noteworthy difference in approach to the life cycle of a product between the business point of view and the ISO-14040 point of view. The business view (Levitt, 1965) puts an emphasis on the evolutionary aspect of a product. It in fact does not look at a product in the singular meaning, but rather at a product as a collective. Product then represents a number of individual products, initially a small number, later a larger number, and in the end again a smaller number. Each of these individual products has a life cycle in its self, in the ISO-14040 sense, from the cradle to the grave. Figure 3.1 illustrates this idea.

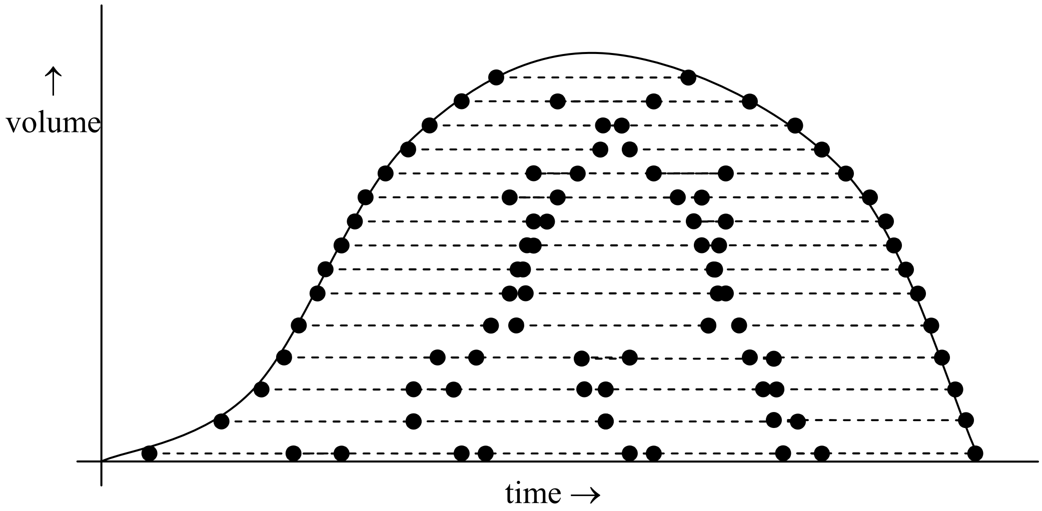

Figure 3.1: The collective product life cycle in the business meaning (solid line) as the aggregation of the individual product life cycles in the LCA-meaning (dashed lines with first bullet denoting the cradle and the second the grave of an individual product).

Having made clear the life cycle concept for our purpose, there is still a variety of ways to address it. Main dimensions here are:

- scope of analysis: cost, CO_2, resources, etc.
- approach: qualitative, semi-quantitative, quantitative, etc.
- factual content: facts only, policy principles, personal opinions, etc.

Below, we will briefly discuss these three issues.

As to the scope, ISO-LCA "typically does not address the economic or social aspects of a product" (p.vi), but rather "addresses the environmental aspects and potential environmental impacts" (p.v). On the other hand, we know of the long history of life cycle costing, of diverse approaches to design a social LCA, and of approaches that combine life cycle information from the environmental domain with that of the economic or social domain, e.g., in eco-efficiency and in sustainability indicators.

Regarding the approach, ISO-LCA does not explicitly state its restriction to quantitative methods, but it implicitly does, witness phrases like “the compilation and quantification of inputs and outputs” (p.2), “evaluating the magnitude” of impacts (p.2), and the central role for the functional unit, the “quantified performance of a product system” (p.4). There is thus no place for non-quantified life cycle approaches in ISO-LCA. But there is definitely a need for these. UNEP’s brochure[6] on the “life cycle approach” sketches this: “a life cycle approach identifies both opportunities and risks of a product or technology, all the way from raw materials to disposal. To do this there is a continuum of life cycle approaches from qualitative (life cycle thinking) to comprehensive quantitative approaches (life cycle assessment studies)” (p.7). And: “life cycle thinking implies that everyone in the whole chain of a product's life cycle, from cradle to grave, has a responsibility and a role to play” (p.3). Recognizing the variety of approaches for a variety of decision-situations, it is to be defined where the place of LCA is. With UNEP and ISO, we restrict it here to those approaches that are primarily quantitative, recognizing that there are important situations (e.g., in product design) in which qualitative or semi-quantitative approaches can be more suitable. We propose that life cycle thinking (LCT) is an overarching term covering all life cycle approaches with a life cycle aspect, also covering quantitative approaches.

Another class of terms is related to action or implementation. For life cycle engineering (LCE), for example, is according to Alting & Legarth (1995, p.570) “the art of designing the product life cycle through choices about product concept, structure, materials and processes”, whereas LCA “is the tool that visualizes the environmental and resource consequences of these choices”. Throughout this document, LCA refers to an analytical tool, a means of getting information and supporting a decision, not for designing products or for stimulating changes.

Related to that, life cycle management (LCM) is “a product management system aiming to minimize environmental and socioeconomic burdens associated with an organization’s product or product portfolio during its entire life cycle and value chain”[7]. Like LCE, this also emphasizes that LCA is a tool (or technique) to help making LCM operational.

Finally, with respect to the factual content, ISO-LCA is somewhat ambiguous. On the one hand, it appears that the word “analysis” has been reserved for the more objective activities (hence “life cycle inventory analysis”), and that less objective aspects have been included as well, but now using terms like “assessment” and “evaluation” (hence “life cycle impact assessment”). That is also a reason for not adopting the term “life cycle analysis”, but to employ “life cycle assessment” by ISO. But on the other hand, ISO-14040 indicates that “decisions within LCA are preferably based on natural science. If this is not possible, other scientific approaches ... may be used or international conventions may be referred to” (p.7). It even leaves open the possibility for including value choices. Other schools employ the term “analysis” for any activity that aims to solve problems and support decisions, even when value judgments play a role. Thus we see terms like “decision analysis”, “multi-criteria analysis”, and “risk analysis”. Following that logic, LCA could perfectly refer to “life cycle analysis”. It is also used in that sense in the acronym CALCAS.

3.3 LCA: foundation, procedure and content

The different meanings of LCA can perhaps be explained with a comparison with the carbon-14 dating and with regression analysis as a form of statistics, where we can discern:

- the theoretical foundation
- the practical way of working

[6] Available for free from http://www.unep.fr/shared/docs/publications/LCM_guide.pdf.
[7] Available for free from http://www.unep.fr/pc/sustain/reports/lcini/UNEPBooklet.ENGprint.pdf.

- the subject for a case study
- the results from a case study

Table 3.1 explains this comparison.

Table 3.1: Comparison of scientific foundation, the practice, the subject and the results for LCA and two other scientific tools.

	C-14 dating	regression analysis	LCA
foundation	isotope decay	least-squares parameter estimation	linear scaling of technologies
practice	mass spectrometer	statistical software	LCA software
subject	a certain object to be dated	a set of data with a probable relationship	a product function/service to be analysed
results	dating of the object	trend line for the data	environmental performance of the product

LCA thus falls into a theoretical part (the method, but often, incorrectly[8], referred to as the methodology of LCA), a set of practical tools (guidelines, software, databases, etc.), and a part related to the actual content, i.e. the subject of analysis and its results.

Most types of analyses consist of a number of ingredients.

- First is a theoretical underpinning, the scientific foundation. Without such a foundation, the analysis can never claim to be a scientific analysis. The use of a horoscope to tell the future can be seen as a form of analysis, but not as a scientific one.
- Second is a procedure: a set of rules for application in practice. In laboratory contexts, the OECD has formulated principles for Good Laboratory Practice (GLP), "a quality system concerned with the organisational process and the conditions under which non-clinical health and environmental safety studies are planned, performed, monitored, recorded, archived and reported" (OECD, 1998, p.7). It is in this spirit that the first *de facto* standard of LCA, SETAC's *Code of Practice* (Consoli *et al.* 1993), is to be understood. The guidelines are based on scientific procedures, but are not scientific statements as such: they provide a bridge between the science and the praxis. As can be seen in OECD's GLP, personnel qualification and reporting issues can be part of the rules.
- Third is the content: empirical material that enters the analysis. For LCA, this is data for inventory analysis and for impact assessment, and it is models for inventory analysis and for impact assessment, understood as mathematical relationships, e.g. climate models and fate models.

Thus, foundation, procedure, and content form the basis of LCA in two ways: shaping the LCA science and the LCA praxis.

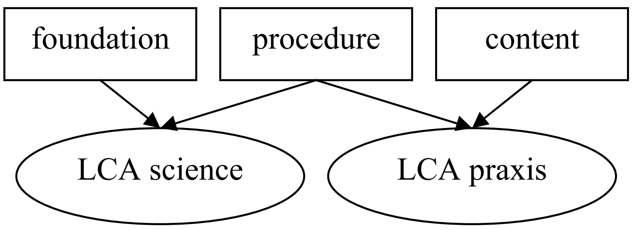

Figure 3.2: The three elements (foundation, procedure, and content) that are needed for LCA science and praxis.

[8] Wikipedia's lemma on methodology stresses the word inflation of using the term "methodology" when the word "method" would be more appropriate (http://en.wikipedia.org/wiki/Methodology).

In the field of environmental analysis, a distinction is often made between analytical and procedural tools (Wrisberg & Udo de Haes, 1998). Analytical tools focus on the use of quantitative or qualitative data, whereas procedural tools assist in implementing and monitoring progress. One could say that a procedural tool focuses on the process of doing something, whatever the result, and that an analytical tool focuses on achieving a result, whatever the way of achieving it. In LCA, we clearly need to consider both aspects, process and result. We deal with numbers, models, calculations, but we also deal with stakeholders that help to define the question, that have insight in how the supply chain works, and that have an interest in applying the results of the analytical part or in implementing the recommendations. Thus, in discussing the foundation of LCA, we must combine aspects from the analytical and the procedural sides.

3.4 The ISO-LCA framework and its limitations

The ISO-14040 & 14044 standard for LCA has been the reference for almost all foundational and practical work on and with LCA. Even though it has been acknowledged that these standards are incomplete, ambiguous, contradictory, etc. (e.g., by Hertwich, & Pease, 1998), they have functioned for a decade in setting the vocabulary, defining the main structure, and providing the context for more elaborate guidelines.

The ISO-LCA framework is shown in the lefthand-side of Figure 3.3. The four phases or stages are described in more detail in the ISO-14040 standards and subsequent standards. It is stressed that "the individual phases of an LCA use results of the other phases", and that "the iterative approach within and between the phases contributes to the comprehensiveness and consistency of the study and the reported results" (ISO 14040, p.7).

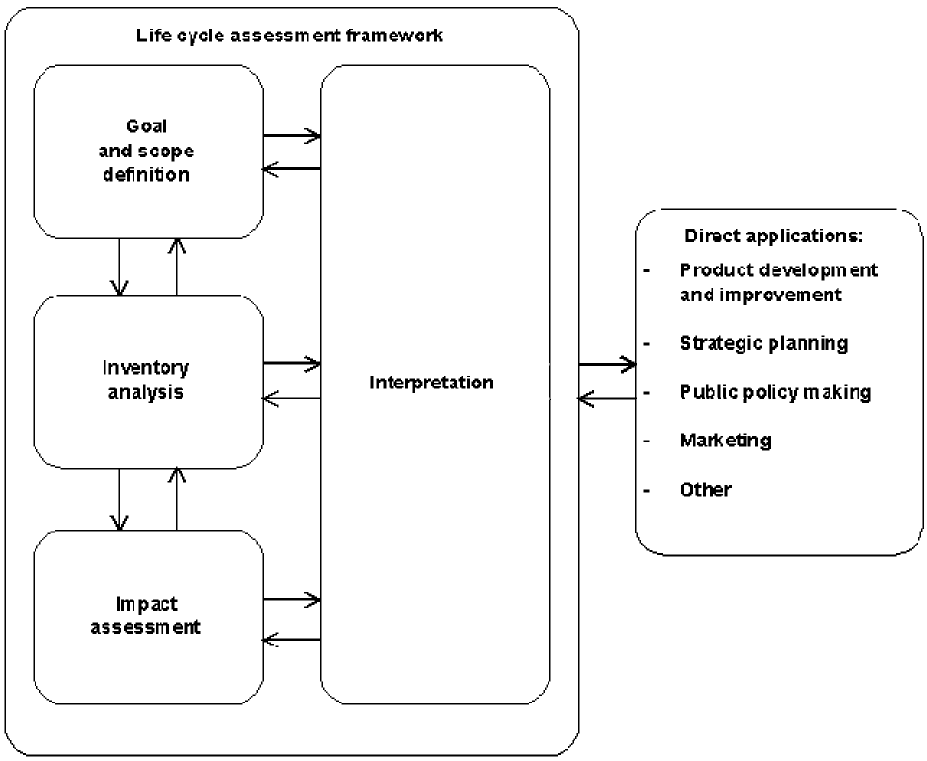

Figure 3.3: The LCA-framework according to ISO 14040.

From even a superficial glance, it becomes apparent that there is much that is not contained in the ISO-LCA standards, or that is included in an unbalanced or even wrong way.

- There is no data, neither process data for inventory analysis, nor characterization factors for impact assessment. That there is no data may be justifiable, e.g. for reasons of not wishing to fix data on technologies that in fact are subject to change.[9] But it obviously makes LCA studies more difficult to execute, and it leads to a larger divergence in results.
- There is no section on the mathematical model of LCA, neither the formulas, nor any standard list of symbols. As Figure 3.4 shows, a list of symbols is a normal element in a scientific discussion in which quantitative elements play a role. As “LCA in practice deals with thousands of quantitative data items that have to be combined in the right way” (Heijungs & Suh, 2002), more guidance on standardizing the modeling aspect as such is needed.
- The standards are not very balanced in their level of detail. Whereas a statement like “The selection of the system boundary shall be consistent with the goal of the study.” (14044, p.8) is not very clear, p.9-10 includes a discussion on the inclusion of specific substance groups, i.e. BOD, COD, AOX, TOX, and VOC.
- There is a lack of unambiguous guidance. For instance, with respect to cut-off, it is said that “several cut-off criteria are used in LCA practice” (ISO 14044, p.8), but no clear guideline is provided. And for allocation, it is stated that “wherever possible” (ISO 14044, p.14) a certain approach should be used, without a specification how to decide on this possibility.
- The standards are the result of different teams of authors. In certain parts of the text, this leads to inconsistencies. Some of these inconsistencies are unimportant and only linguistic (e.g., on page 2 of the 14040 standard, “life cycle inventory analysis” and “life cycle impact assessment” are defined, while on the same page, they are used in a sentence like “either the inventory analysis or the impact assessment”, so without the “life cycle”). More problematic are cases like for allocation, where the first step of the allocation procedure “is not part of the allocation procedure” (ISO 14044, p.14). Another problematic example is the reference flow, which is in ISO 14040 (p.2) a “measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit”, while in ISO 14049 (p.6), an example is given where it is “15 daylight bulbs of 100 lx with a lifetime of 10000 hours”, apparently needing no electricity whatsoever.
- The standards contain factual errors. For example, 14044, p.40 mentions GWP100 as a “category indicator result”, and even states in an example that the “total GWP” of CO_2 is “2750 kg CO_2-equiv.”. Obviously, the GWP of CO_2 is 1, by definition; it can never be 2750. See also Heijungs (2005) for the use of abbreviations, symbols, and units.
- There is no scientific foundation. Although it is stated that the LCA must be “scientifically and technically valid” (ISO 14044, p.31), no reference is made to the standard textbooks on physics, chemistry, toxicology, economics, etc., or to frontier research documented in scientific journals. So, although there might be a scientific foundation of the standards, it is not demonstrated. And in science, it is demonstration that counts.

[9] OECD’s GLP documents also do not state data.

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Nomenclature

$\varepsilon = \eta_{\mathrm{I}}$	First Law efficiency (dimensionless)	$\dot{E}$	exergy from mechanical work or electricity (W)
$\eta = \eta_{\mathrm{II}}$	exergy efficiency (dimensionless)	$\dot{E}_q$	rate of heat exergy (W)
$(\ )^+$	convention positive into the system	$\dot{E}_y$	rate of transformation exergy (W)
$(\ )^-$	convention positive out of the system	EXV	exergy value (Δk^0 in [4]) (J/kg$_F$)
T	temperature (K)	J_{cz}	coenergy ($= U_{cz} + P_a V - T_a S$) (J)
V	volume (m^3)	h	specific enthalpy (J/kg)
P	pressure (Pa)	h_{cz}	total specific enthalpy (J/kg)
S	entropy (J/K)	k	specific coenthalpy ($= h - T_a s$) (J/kg)
H	enthalpy (J)	k_{cz}	total specific coenthalpy ($= h_{cz} - T_a s$) (J/kg)
$\dot{Q}$	rate of heat transfer (W)	s	specific entropy J/(kgK)
U_{cz}	total internal energy (incl. kinetic and potential energies) (J)	Θ	Carnot factor $= 1 - (T_a/T)$ (dimensionless)

The authors did not find in the literature examples of successful introduction of an exergy concept in a legal framework. It is however worth mentioning proposals [2,3] exergetic costs but the present approach did not try to use exergy costing.

Similarly, the scarcity of resources, linked to the fact that

Figure 3.4: Excerpt with nomenclature and symbols in a typical article (taken from Favrata et al., 2008).

In conclusion, the ISO standards for LCA have served a definite function in facilitating the communication between scientists, practitioners, and others by providing a vocabulary, and in pointing out points of agreement and disagreement. But they have also a limited meaning or even failed in aspects such as not providing a scientific basis, not providing the intended clarity that is needed for a routine application, and not providing the indispensible data and formulas.

3.5 Towards a scientific framework for LCA

A framework like in Figure 3.3 is a procedural framework: it describes steps, activities. It has been shown already that it is not a scientific framework. What a scientific framework is anyhow, is a philosophical, and not a technical question. The "scientific method", as it has developed from Bacon and Descartes onwards, is an example of a scientific framework. Here, the elements are observation, hypothesis formation, hypothesis testing, etc. This is a framework of scientific activity of a general nature. For a specific field of study, a more specific framework can be derived from this general framework. For instance, when we do a statistical test, we can follow a procedural framework like the following (Siegel, 1956):

- stating a hypothesis;
- selecting a test;
- specifying a significance level;
- computing the test statistic and the region of rejection of the hypothesis;
- deciding on the result of the test.

And in the context of modelling, another framework is usual (Jørgensen, 1986):

- observation of phenomena;
- formulation of a hypothesis;
- deduction of verifiable predictions;
- experimental or observational testing of predicted phenomena;
- evaluation of the hypothesis.

Again, these two frameworks are not a scientific framework as such, but their construction has been embedded in the sciences themselves, where the different elements (hypothesis formation, hypothesis testing, etc.) have a clear place in the scientific method and in the branch of science in which it is applied.

It is now a challenge to design a scientific framework – or better: a science-based framework or a scientific foundation – for LCA. Elements that need to be addressed in this are primarily the following:

- the foundations of physical science (conservation of mass, thermodynamics, ...);
- the foundations of economics (market equilibrium, ...)
- the foundations of decision analysis (multi-attribute utility theory, ...)
- the foundations of earth and life science (toxicology, climatology, ...)

In Chapter 5, we will start with sketching such a framework and its ingredients.

3.6 The role of objective facts and subjective values in LCA

We end this chapter with a brief discussion on the role of facts and values in LCA. In the short history of LCA, we may discern quite a number of issues on which the alleged or desired degree of "hard facts" has been of concern. SETAC's first report on LCA (Fava et al., 1991) stated that LCA "is an objective process" (p.1), and that the impact assessment is "a technical, quantitative, and/or qualitative process" (p.1). In subsequent work, and notably in the ISO-standards, the presence of value judgments has been acknowledged, although still limited to the impact assessment. But also the "soft" nature of certain elements in inventory analysis is already clear, when we acknowledge essentially arbitrary decisions on cut-off and allocation.

Science always starts with observations, phenomena, facts. But sooner or later, arbitrary elements will have to come in: the logical postivism of the Vienna circle has been abandoned by the present philosophers of science. What we define to be a mammal or a fish is a question of definition, not of facts *per se*. And whether we decide to label a difference between two groups as "statistically significant" depends on the arbitrarily chosen significance level. Thus, whenever we discuss a "scientific" framework for LCA, we should not be afraid of introducing arbitrary elements and values, as long as we acknowledge this (cf. Hofstetter, 1998). The use of subjective utility functions can help to progress economics, and so can it help to progress the science of LCA.

On the other hand, acknowledgment of the fact that LCA, or indeed any other scientific tool or theory, contains arbitrary elements should not induce one to fall in the post-modernist trap of denying the existence of reality or objective facts. The challenge is to construct a theory and a way of working that is sufficiently science-based, but that also contains a sufficient amount of subjective and well-recognizable aspects.

Facts and values enter at many places in the science and praxis of every field of applied science. To be more specific, they show up in the foundation, in the procedure and in the content. Figure 3.5 illustrates this.

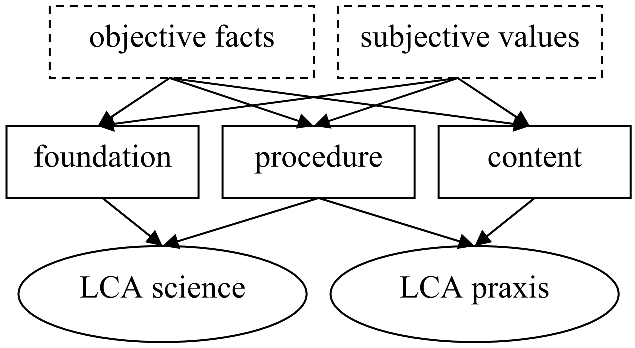

Figure 3.5: Objective facts and subjective values provide the basic material for the three elements of Figure 3.2.

4 THE TWO ELEMENTS COMBINED: LIFE CYCLE ANALYSIS FOR SUSTAINABILITY

CALCAS is a "Co-ordination Action for innovation in Life-Cycle Analysis for Sustainability", and it hence combines both elements: life cycle analysis and sustainability. In this chapter, these two elements are combined and contrasted in order to set the focus of the scientific framework of the final part of this report.

4.1 LCA and SA, deepening and broadening, reducing and simplifying

In Section 3.2, it was seen that LCA is typically restricted to environmental aspects, and that it does so in a simplified way[10].

But as we start from the position that SA covers more dimensions or aspects than LCA, we first note that an SA is "broader" than an LCA. Thus, in order to move from LCA to SA, we need to "broaden" the scope of LCA. Adding the social and economic dimension to environmental LCA will do so. This does not necessarily mean that an SA will yield more results, more indicators, and more numbers. For instance, the New-LCA might produce results in the form of an eco-efficiency indicator (Huppes & Ishikawa, 2007). Such an indicator includes economic and environmental information, but in a combined way.

The CALCAS project deals further with deepening LCA. ISO-LCA is a simplified analysis, as it primarily focuses on the physical relationships between the processes in the life cycle. If we need extra electricity to run a TV, the power plant needs extra fuel, and that's it. Although such relationships are driven by physical necessities, they are sometimes considered as environmental links, as environmentalists sometimes see connecting flows such as electricity, iron and waste as "environmental links". In reality, such mechanisms are more complicated. For instance, there are socio-economic mechanisms that co-determine the relationships between unit processes. Thus, the primary physical (or "environmental") mechanisms within the system are deepened to include social and economic mechanisms. In addition, they are deepened in other senses. For instance, they may include dynamics (whereas ISO-LCA typically excludes dynamics), or they may become non-linear (whereas ISO-LCA is based on linear technologies).

Broadening and deepening suggests that New-LCA is more complicated than ISO-LCA. This is not necessarily true. A small excursion to the IPCC GWP-model can help to illustrate this. The GWP-model attempts to give insight into the effects of greenhouse gas emissions. It is a complicated model, but one of its core results is a list of GWP-values. During the years, the model has been elaborated, becoming broader and deeper, yielding updated – more accurate – GWP-values. But although the model has become more complex, the use of these GWP-values has not changed. They can still be used in the same way as before. We think that the same is true for New-LCA. Using New-LCA as a tool for SA is not necessarily more complex than using ISO-LCA for environmental analysis.

Starting from the other side: an LCA is life-cycle based, but an SA need not be. Sustainability indicators for countries in most cases reflect what is going on in that country in a certain year. They tend to ignore what is imported from or exported to abroad, and they in general do not account for

[10] After all, LCA is a model, and a model is a simplified representation of something; see also Section 5.1.4.

future emissions due to today's production. Likewise, sustainability reports from companies typically focus on the company's practice as such, and do not or only partially address the supply chain or the consumer and post-consumer aspects of their products.

In the CALCAS project, the central concept is "Life-Cycle Analysis for Sustainability". This means that the focus is on what might be called life cycle sustainability analysis (LCSA; see Klöpffer, 2008):

- LCA with a broader focus of indicators;
- SA with a broader system boundary.

In the rest of this report, LCSA will be the prime object of discussion, although we will often use the terms "LCA" and "SA" to stress either the life cycle character or the sustainability character.

4.2 LCA versus SA, scope, strengths and limitations

LCSA is thus a life-cycle based SA, or stated in a different but equivalent way, it is an LCA that covers all three dimensions of sustainability. But this does not necessarily mean that SLCA supersedes the traditional LCA and SA. Sometimes, there may still be reasons to carry out an SA without a life-cycle perspective, or to carry out an LCA on environmental issues alone.

LCA traditionally focuses on the environmental dimension. As such, it has been defined in terms of physical exchanges between processes, and between a process and the environment. Mass balances are supposed to provide checks for consistency of data. Indeed, any chlorine that is taken in by a process, e.g., in the form of PVC, must leave it, at least in the long run. This output can be in the form of products, or in the form of releases to the environment. Typical LCA data sets report everything in physical units: kg of material, MJ for energy, km for transport services, etc. Once we start to broaden LCA by a social and an economic dimension, this physical dominance starts to disappear. This is a disadvantage of broadening LCA. The usefulness of present-day databases is restricted to the narrow definition of LCA, and mass balances no longer help to establish data inconsistencies. On the other hand, present-day LCA is by its focus on a product-oriented system sometimes too encompassing. Benchmarking of companies and countries, for instance, need not necessarily assume a life cycle perspective. So, there remains room for purely environmental LCA and for SA that is not life-cycle based.

Broader LCA includes more dimensions of sustainability than the environmental one only. Present-day LCA is by its restriction to environmental affairs less useful than a sustainability analysis. Many companies and countries report on sustainability, but not on LCA. Companies and countries consider the environment as an important factor that should be taken into account, but not as the prime target of decision.

A deeper LCA is a more realistic LCA. The present-day assumptions of the LCA model have served a role in paving the way for the idea of LCA and of setting the agenda for research for a more realistic model.

An LCA that is better founded is an LCA that is more robust to criticism and that is more justified to claim the result of scientific scrutiny. Links to established disciplines, from engineering to economics, and from systems analysis to decision theory, strengthen this claim. Science has never had the final word in decisions. But scientifically based information can make the most lasting contribution to such decisions.

4.3 Getting information: data, models and indicators

In a traditional sustainability analysis, sustainability indicators may be shown that represent the status of a certain country, company, etc. Such indicators are based on data that represents the knowledge we have for the issue at stake. However, an indicator is an indicator for something, and data alone is in many cases not enough. So we have to address questions such as:

- what is the data for LCSA?
- what are the indicators for LCSA?
- how to move from data to indicator?

If we want to know how "big" a person is, we may measure his weight. In that case, the body weight is the data, and it is supposed to be an indicator of the size of the person. Other indicators of the same aspect may be considered. For example, the length of the person is another indicator of the size. Both indicators are quite simple, and in fact provide a one-to-one correspondence between data and indicator. More complicated indicators are the volume of the person, which combines elements of size of three dimensions, or perhaps an even more complicated form in which length and weight are combined in a certain way, say multiplying the square root of the length with the logarithm of the weight.

This separation between the things which are known (or supposed to be known[11]) and the things which we wish to know is an essential step in discussing the model structure of LCA, or of science in general, and even of common-sense. In many cases, we know certain things, and we want to know other things. A model provides the necessary connection. And even in those cases where the data appears to be the indicator, and the model is hence an empty step, the explicit decision that the data is the indicator is still a crucial step. Figure 4.1 illustrates this idea, and Table 4.1 gives four examples.

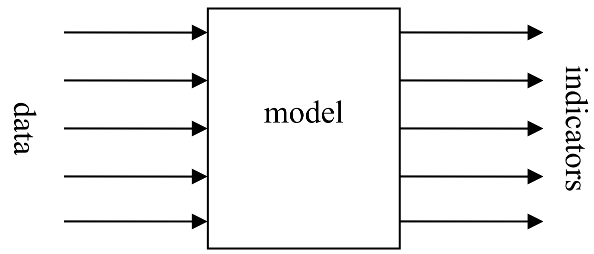

Figure 4.1: Data, model and indicators. The data provides measurable aspects of the system, while the indicators represent the aspects that we wish to know. The model converts .the data into the indicators.

Table 4.1: Four examples on data, model and indicators. In the first one, the data coincide with the indicators, in the second one, the data are transformed in a very simple way, and in the third and fourth example, the model is quite elaborate.

	data	model	indicator
nutritional value of food	content of energy, proteins, fats, etc.	no model	content of energy, proteins, fats, etc.
car efficiency	fuel use, kilometers driven	simple division	fuel use per km
intelligence	answers to questions	IQ-table	IQ
environmental	unit process data,	LCA-rules and -	inventory table,

[11] This touches on a philosophical debate whether it is possible to know anything at all (skepticism), whether we really know things that others have been finding out (most knowledge is authoritative), and whether things we measure are the prime source of information, or that they presuppose some theoretical frame (observations are theory-loaded). These issues will be ignored at this place.

performance	characterization factors	formulas	impact table

The distinction between data and indicator is an important one. Several authors suggest that one can measure sustainability (Figge & Hahan , 2004; Spangenberg, 2002), although there are also authors who write on "measuring the immeasurable" (Bell & Morse, 1999; Böhringer & Jochem, 2007). As a matter of fact, one cannot measure sustainability, sustainable development, environmental quality, biodiversity, happiness, wealth, etc. But one can define such concepts, and analyze their relationship with observable phenomena[12]. This relationship can then be formalized in a model structure, which is a set of rules (e.g., on what counts as a species) and a set of mathematical formulas (e.g., the relation between species density and biodiversity). IQ-tables and the rules and formulas of ISO-LCA are examples of such model implementations of the general concept of intelligence and LCA respectively.

In a model set-up, Figure 4.1 can be formalized as

$$y = f\left(x\right)$$

where x denotes the data, y denotes the indicator, and $f()$ expresses the assumed relation between data and indicator. The functional form of the relation $f()$ between x and y is supposed to reflect the definition of the concept. As an example, the indicator for car efficiency (see Table 4.1) is constructed as

$$\text{car efficiency} = \frac{\text{fuel use}}{\text{kilometers driven}}$$

The functional relationships for LCA is obviously much more complicated. It will be discussed in more detail in Chapter 5.

[12] Again, philosophical questions may arise as to what is observable, and what is derived from observations. Strictly spoken, a voltmeter does not measure a voltage. Rather, it offers the reading of a length, which is supposed to reflect a magnetic field, which is supposed to reflect a current, which is supposed to reflect a voltage. Thus, the length is an indirect indicator of the voltage through a number of modelling steps, and one does not measure voltage, but length. Similar arguments may be held for the measurement of other "observables", such as time, mass, temperature, toxicity, employment, etc. The boundary between data and indicator is not so clear, and many data items are in fact already the result of models.

5 GENERAL MODELLING FRAMEWORK

This chapter presents a general framework that is supposed to be the implicit basis of many or perhaps even all models of life-cycle based sustainability analysis, at least of those that address the interaction between economic systems and environmental systems. The framework is developed here on the basis of a discussion of theoretical considerations and experiences with a number of concrete models.

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

5.1 Interactions between the economy and the environment

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

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

5.1.1 The material basis of production and consumption

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

Two important exceptions we wish to introduce here are the pioneering work of Robert Ayres and co-workers and that of Nicholas Georgescu-Roegen, both around 1970. The concept of the materials balance principle, or stated in more familiar terms, the law of conservation of mass, has been brought into the discussion around economic production and environmental degradation by Ayres & Kneese (1969). They constructed a theory and accounting scheme for the mutual relationship between industrial producers, and their relationship with consumers on the basis of the conservation of mass. The other development is connected to the second law of thermodynamics, which Georgescu-Roegen (1971) refers to as “the entropy law”. Producers and consumers are not a simple cycle of agents of which the former converts labour into products, and the latter converts products into labour. Instead, an inevitable degradation of quality occurs during this process, one that is deeply rooted in the thermodynamics of irreversible processes.

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

An analysis of the inflows and outflows of materials and energy at the process level is depicted in Figure 5.1. It is a combination of the materials balance principle and the entropy law and it indicates the necessity of absorbing raw materials and fuels and of producing by-products. The materials balance principle ensures that these outflows of high entropy must at least in part have a material character, in which case we speak of waste flows or emissions of pollutants.

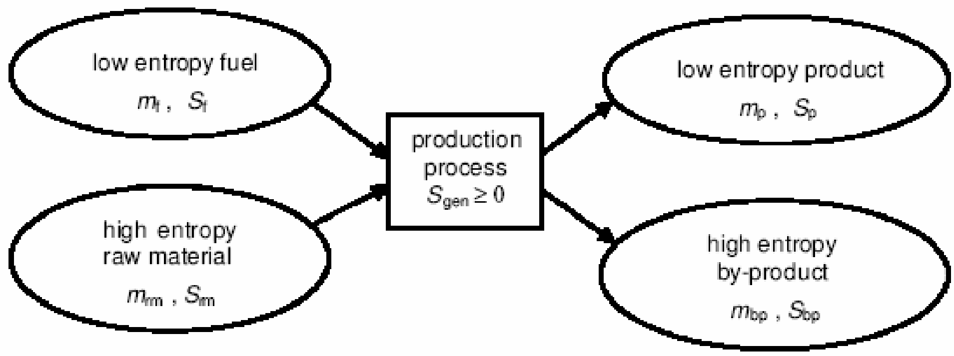

Figure 5.1: The thermodynamic structure of an industrial production process in terms of mass (m) and entropy (S). Source: Baumgärtner & de Swaan Arons (2003), p.115.

Figure 5.1 has been drafted for a production process, but equally well applies to larger systems, such as installations, plants, companies, supply chains, product chains, countries, and even to the entire world, containing people, ecosystems, and our production systems. As such, it illustrates the scientific foundations of two major problems of production and consumption: resource depletion and waste and pollutants generation. Effectively, it shows that "zero emission" cars or industries (Pauli, 1997) cannot exist.

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

5.1.2 Production, consumption, and environmental pressure

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

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

These are combined to form a mathematical expression:

$$I = PAT$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\mathbf{T} = \mathbf{T}_{env}\mathbf{T}_{tech}^{-1}$$

where $\mathbf{T}_{env}$ is the environmental specification of the technology (like the CO_2 emissions per process or sector), and $\mathbf{T}_{tech}$ is its inter-industry specification (like the electricity requirements per process or sector). In IO-based LCA, we have $\mathbf{\Lambda} = \mathbf{B}(\mathbf{I}-\mathbf{A})^{-1}$, where **I** is the identity matrix, and the term in parentheses with the –1 is the Leontief inverse[13]. We can translate this as

$$\mathbf{T} = \mathbf{T}_{env}\left(\mathbf{I} - \mathbf{T}_{tech}\right)^{-1}$$

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

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

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

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

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

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

In describing the I of the IPAT equation, we already introduced the distinction between environmental pressure, like CO_2 and pesticides, and environmental impact, like climate change and biodiversity. Within the context of life cycle impact assessment, discussions about environmental mechanisms, cause-effect chains, and midpoint- and endpoint-oriented models have been discussed extensively; see Figure 5.2 for an example.

[13] The symbol **A** (and hence $\mathbf{T}_{tech}$) has a similar but not exactly identical meaning in LCA and IOA. See Appendix B of Heijungs et al., (2006) for a discussion of the near-perfect similarity, and an explanation of the occurrence of **I** and the minus sign in the IO-form.

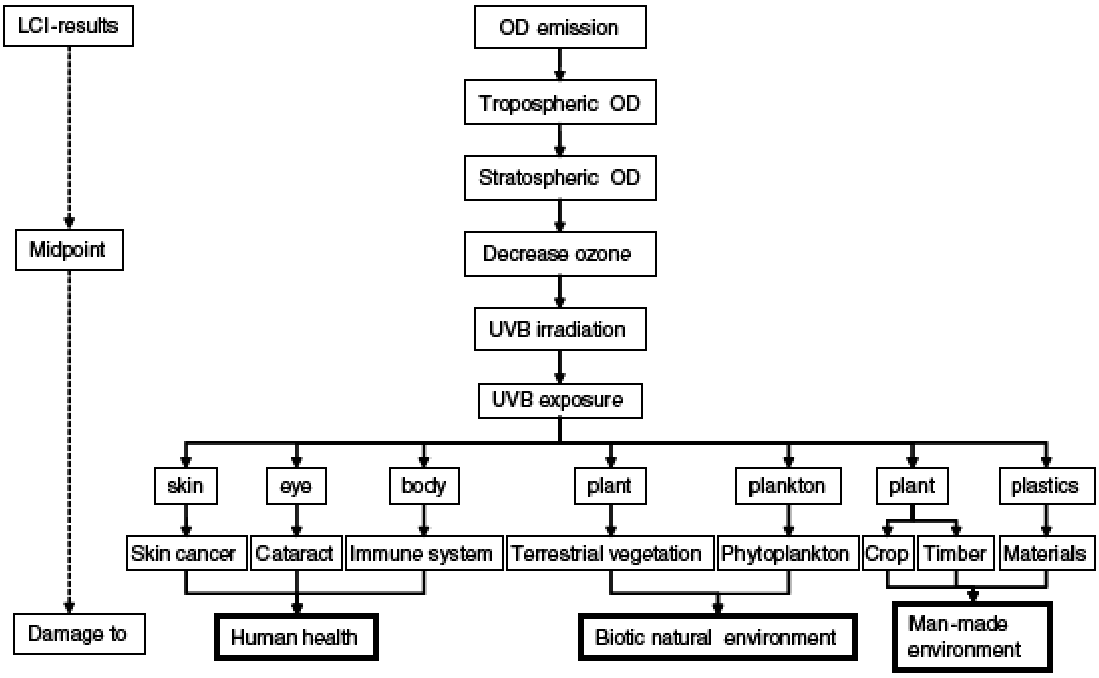

Figure 5.2: Example of a cause-effect chain linking environmental pressure (in this case ozone depleting emissions) through midpoints (ozone layer depletion) to endpoints (damage to human health, etc.). Source: Jolliet et al. (2004), p.398.

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

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

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

The relation between pressure and impact is discussed in a more comprehensive framework in terms of the so-called DPSIR-framework (see, e.g., Smeets & Weterings (1999); see Figure 5.3). This is a framework that considers the relation between economy and environment to be divisible into five aspects:

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

The intermediate S for the state of the environment is an aspect that is often accounted for in multimedia fate and exposure models, whereas the impact itself is indicated using dose-response[14] relationships.

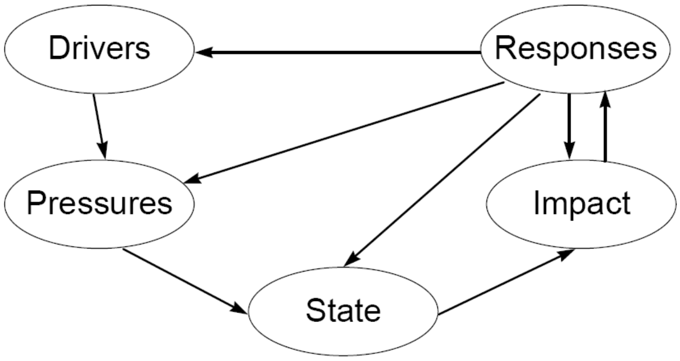

Figure 5.3: Overview of the DPSIR framework. Source: Smeets & Weterings (1999), p.6.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

[14] Notice that the term "response" is here used in a different sense as one paragraph earlier. Response is a general term, which combines with terms like "question", "stimulus", just like we have word pairs such as "cause-effect" and "action-reaction". In some fields of science, the term "response" has obtained a dedicated meaning, for instance in toxicology ("dose-response") and in political science (where politicians are assumed to "respond" to new situations).

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

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

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

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

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

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

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

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

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

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

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

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

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

Some aspects not yet fitting in the inventory-environmental effects framework require special attention, being relevant and not having a systematic place in the analysis. One salient example is risks, as calamities resulting from unplanned but to some extent predictable deviations in industrial operations. Partly, such aspects may be covered in the specification of economic activities, like traffic accidents in truck transport, linked to adequate mechanisms like casualties. Partly, they require other environmental effect routes, like for the fall-out after the Chernobyl-like accidents.[15] Partly, they may be treated as additions to inventory specifications, like casualties and emissions from fire accidents. One central question here is how to structure such surely relevant effects, either incorporating them in a broad definition of environmental effects, or giving them a place as a separate category of damages, or as damages which may occur through non-environmental mechanisms, as social damages. See Simonson et al. (2002) for an example on the treatment of fire accidents.

There is still something that does not fit. On the one hand, ISO-LCA represents a model in which information flows in a linear way:

- in the goal and scope definition the LCA-practitioner provides the functional unit (**f**);
- in the inventory analysis the LCA-practitioner specifies the system and provides the data that represents it ($\mathbf{T}_{\mathrm{tech}}$ and $\mathbf{T}_{\mathrm{env}}$); these data are combined with f to yield the inventory table (**g**);
- in the impact assessment the LCA-practitioner specifies the data on impact categories and optionally on normalization and weighting (**Q**, **w**); these data are combined with **g** to yield the impact table (**h**) and optionally a weighted index (*W*);
- in the interpretation the LCA-practitioner analyzes these results (**g**, **h**, *W*) as to robustness, significance, etc.

This suggests a flow from goal and scope definition to interpretation through at least inventory analysis and optionally impact assessment. The ISO-framework for LCA (Figure 3.3), on the other hand, show arrows that go forward and backward. ISO 14040 (p.7) explains that by pointing out that "LCA is an iterative technique. The individual phases of an LCA use results of the other phases. The iterative approach within and between the phases contributes to the comprehensiveness and consistency of the study and the reported results." Finally, as the DPSIR framework (Figure 5.3) shows, there is no simple cause-effect in socio-economic systems. Neither is it there in natural systems. Every effect can be the cause of a new effect, and due to feedback structure of the systems, every effect can affect its own cause. Altogether, we can refine Figure 3.3 into Figure 5.4, where solid arrows indicate the normal information flow, and dashed arrows indicate both the procedural flow but also the information flow of aspects that are not part of traditional LCA. Such aspects include:

- rebound effects (e.g., energy-efficient lamps are switched on longer, so inventory data can lead to a readjustment of the functional unit);
- system expansion (the co-products of a multifunctional process in the inventory analysis can be treated by "expanding the product system to include the additional functions" (see ISO 14044 p.14), thereby effectively redefining the functional unit);
- mitigating measures (e.g., the current policies to mitigate climate change (impact assessment) will effect the technologies (inventory analysis));
- policy measures (e.g., an LCA can lead to an – at the time of the study – unforeseen ecotax (interpretation) with implications for the assumed use (goal and scope definition)).

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

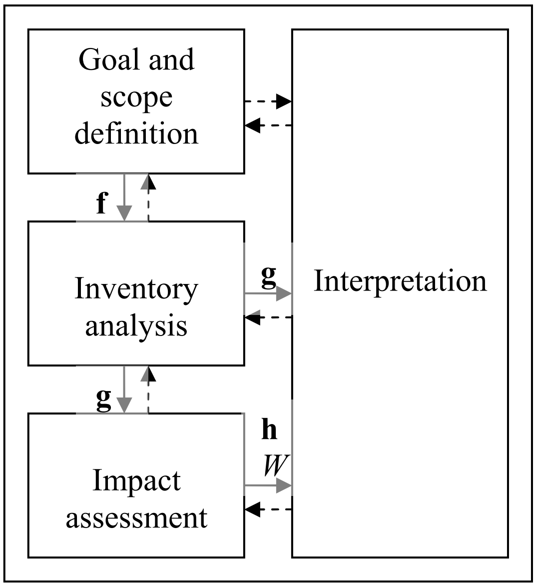

Figure 5.4: Refinement of the ISO-framework for LCA, with solid arrows indicating information flows (functional unit **f**, inventory table **g**, impact table **h**, and weighted index *W*), and dashed arrows indicating both the iterative procedure of LCA, but also the information flows to be added in deepened New-LCA.

5.1.4 Models for environmental decision-support

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

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

A model can be understood in different ways. According to some definitions, a model is a simplified representation of a real system. The purpose of the model can then be to visualize the structure of the real system (see Figure 5.5). Of course, the term “structure” is an ambiguous one. In the context of visualization it refers to a morphological meaning (like for a DNA model), or to a geometrical meaning (like for a model of the solar system).

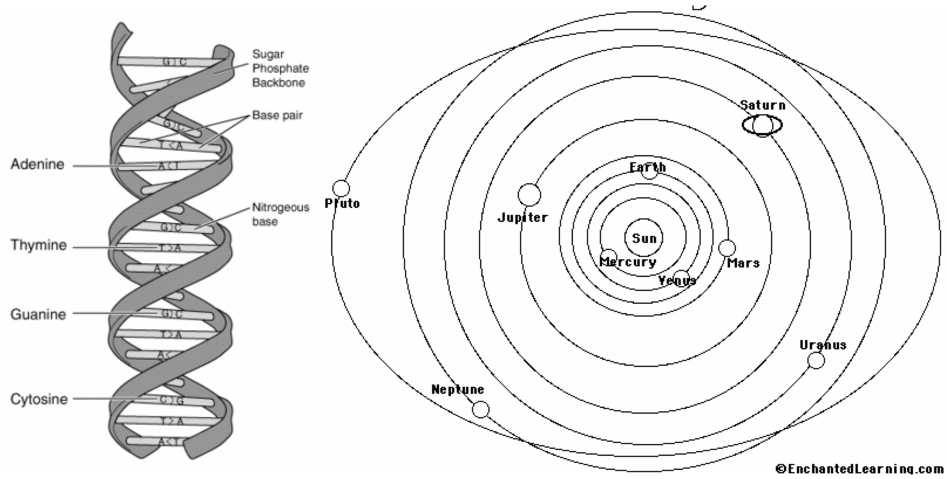

Figure 5.5: Two examples of a model as a visual representation of the structure of the real object.

A more important class of models is those that represent the behaviour of the real system. Behaviour, again, is a term that can mean many things. In any case, it has to do with changes: autonomous changes in time (such as the course of the planets), or exogenous changes due to perturbations (like what happens if a comet disturbs the smooth orbits of a planet). Changes can be included in models through designing dynamic[16] models. But that is not necessary: it is well possible to study the influence of a comet through a comparative static analysis, comparing two versions of the right picture of Figure 5.5, neglecting all transient states. Nowadays, dynamic LCAs refer to LCAs in which the temporal dimension is taken into account in one way or another; see also Section 5.7.3.

5.2 General modelling principles

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

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

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

5.2.1 The purpose of models for sustainability analysis

Decision-makers want to be informed, and scientists develop information tools and calculate indicators. In the process of choosing or developing the right tool for a concrete decision, an issue that shows up again and again (Heijungs, 1997; Frischknecht, 1998; Weidema et al., 1999; Tillman, 2000; Curran et al., 2001; Weidema, 2001; Werner & Scholz, 2002; Guinée et al., 2002; Ekvall & Weidema, 2004; Ekvall et al., 2005; Ekvall & Andrae, 2006) is the distinction between

[16] The term "dynamic" often creates a lot of unclarities. Etymologically, it refers to the Greek Δυναμική, which is usually translated as "force". But since Newton's theory asserts that a force leads to accelerated motion, dynamics is almost naturally associated with the behaviour of a system in time. As such, mathematicians study "dynamic systems", where a temporal parameter is of critical importance, but where no concept of force occurs. Reminisences of the original meaning can be found in music, where dynamics refers to the softness or loudness of a note.

consequential and attributional LCA. A large variety of words has been coined to refer to these terms: prospective vs. retrospective, change-oriented vs. accounting, etc. Quoting from Ekvall & Andrae (2006, p.345):

- Attributional methodology[17] for life cycle inventory analysis (LCI) aims at describing environmentally relevant physical flows to and from a life cycle and its subsystems.
- In contrast, consequential LCI methodology aims at describing how the environmentally relevant physical flows to and from the technosphere will change in response to possible changes made within the life cycle.

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

The emergence of the distinction between attributional and consequential models has been theoretical mainly, although some practical implementations have been published (e.g., Weidema et al., 1999; Ekvall & Andrae, 2006). There are good reasons for the lag of the practice: most LCI databases, for instance, provide average data and most impact assessment factors are a mix of average and marginal factors[18], so that all attempts for being pure are restricted to small exercises.

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

In this document we will investigate:

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

Section 5.7.1 elaborates on these issues.

5.2.2 The distinction between a system and its environment

In ISO-LCA, the flow diagram (Figure 5.6) is a visual means that helps to clarify the choice of the system and its environment. One might argue that the system is in this case the product life cycle, and that the system's environment is the rest of the universe, in particular the rest of the economy and what we usually call "the natural environment". However, that is not correct. In systems theory, the system environment is supposed to be very large; so large in fact that it is not affected by the system. The environment is an unlimited source and sink of materials and energy, hence the environment is unchangeable. That is clearly not the case in LCA, where the prime purpose is to model changes in the environment, like climate change or acidification, as a result of the functioning of the product system.

[17] See our earlier comment on the inappropriateness of the term "methodology" in this context. Better terms are method, analysis, model or tool.

[18] For instance, all LCI databases that we are aware of contain average data, while GWPs are based on marginal models.

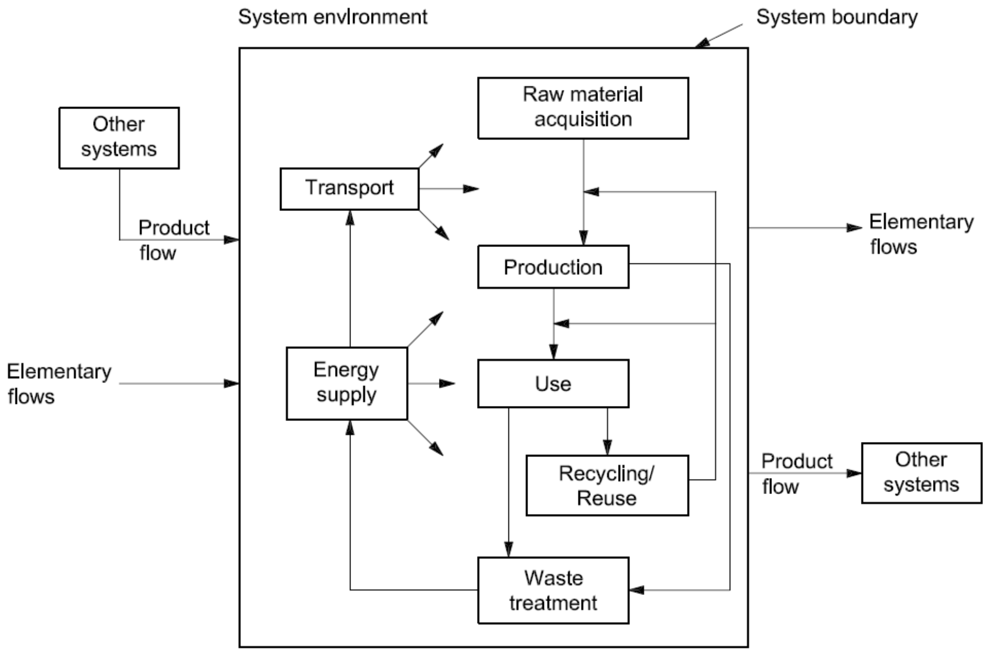

Figure 5.6: Example of a flow diagram in ISO-LCA. Source: ISO 14040 (2006), p.10.

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

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

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

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

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

In LCA, the economic subsystem's components are usually indicated by boxes in a flow diagram (Figure 5.6).

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

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

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

5.2.4 The relationship between the components

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

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

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

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

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

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

When discussing the allocation problem and related questions on system boundaries, it is useful to distinguish between attributional and consequential LCA (see Sections 5.2.1 and 5.7.1)). An attributional LCA typically includes, and is limited to, the whole life cycle from cradle to grave. Allocation problems are typically solved through partitioning of environmental burdens in proportion to some property of the products: the economic value, mass, volume, etc. (Tillman 2000). The system boundaries in a consequential LCA, in turn, are defined to include the activities contributing to the environmental consequences of a change, regardless of whether these are within or outside the cradle-to-grave system of the product investigated. Allocation problems are often avoided by expanding the system boundaries to include affected processes outside the cradle-to-grave system (Tillman 2000).

5.2.5 The relationship between the system and its environment

In thermodynamics and in general system theory, it is customary to distinguish three types of system:[19]

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

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

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

5.3 Modelling mechanisms

As explained above, a systems approach means distinguishing elements, and connecting these elements by mechanisms. In the present context, we can distinguish many types of mechanisms. We will explain this with a simple example. For that, we will take a phenomenological point of view.

5.3.1 Mechanisms as a connecting link between activities

Within the context of LCA, a mechanism is in the first place a causal relationship that connects the level of two activities. Here, the term level refers to the size or intensity of the activity. Obviously, the activity of watching TV is connected to the activity of producing electricity. If we turn off the TV, less electricity is demanded from the electric power plant, but it is still producing electricity, for other types of demand. So, the activity level watching TV is connected to the activity level of producing electricity; see Figure 5.7.

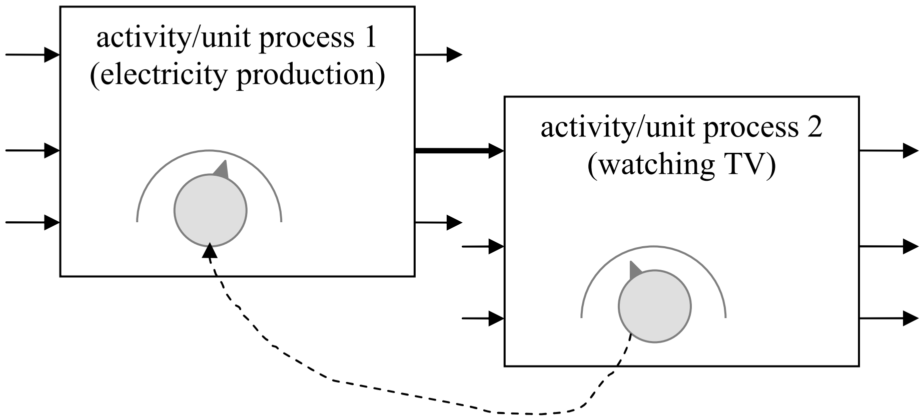


Figure 5.7: Illustration of the causal connection between the activity levels of two activities (unit processes) in a system that represents a life cycle. The two processes are connected by a physical flow, in this example electricity (bold arrow). In ISO-LCA, the two activity levels are connected (dashed arrow) directly by this physical flow. In New-LCA, this connection is made more sophisticated, and can involve a variety of technological, economic and cultural mechanisms.

It obviously is a partial connection that is mainly in one direction. With partial, we refer to the fact that the electric power plant's level is only partially determined by our TV watching. If we switch off the TV, the power plant will only decrease its level, it will not be switched off as well. And with the directional statement, we refer to the fact that the causation is mainly from the TV to the power plant. If the power plant's activity level is increased, we will not turn on the TV.

One could argue that the connection between watching TV and producing electricity is a physical mechanism: TVs use electricity. But as we consider TV use and electricity production as activities (or in LCA jargon: processes) that reside within the domain of technology, we will conceive their causal connection as a technological mechanism, albeit with a physical counterpart.

In fact, in LCA language, one often refers to electricity as an "economic flow", to distinguish inter-process flows from flows between a process and the environment, that are often regarded as "environmental flows", "environmental interventions" or "elementary flows". This is supposed to stress that the exchange of an economic flow is a transaction between two actors in the economic system, regardless the question if the flow has a positive money value, a negative value, or no value. Goods (such as steel or electricity) can flow between a supplier and a customer, and will be accompanied with a monetary flow in the reverse direction. "Bads" (such as radioactive waste) can also flow between a supplier and a customer, but these will be accompanied with a monetary flow

in the same direction. Finally, there are "free goods" which flow between a supplier and a customer, but for which there is no accompanying monetary flow, at least not directly visible on a "pay per item" basis.
Free magazines in trains or airplanes and freely usable waste bins in shopping streets are examples.[20] Thus, besides a physical counterpart, the technological causal connection between using a TV and producing electricity has an economic counterpart.

The arena of mechanisms is much wider. Using a TV also 'causes'[21] the prior production of the TV, and it likewise will yield a broken TV after a couple of years, causing[22] the need of waste treatment activities. Associated with the use of a TV is a whole series of broadcasting activities, requiring studios, electricity, costumes, and so on. Many TV users are subscribed to a programme guide, which needs to be produced, distributed, and discarded after use. In a different direction, we know that TVs are used in a specific personal surrounding, for instance with the person watching seated on a leather sofa, eating popcorn meanwhile, and drinking a coke. In that sense, the use of a TV causes a whole array of economic activities that relate to production of food, drinks and furniture, and its waste processing. Still more remote is the connection between watching a commercial on TV and buying the thing that was being advertised. Or between watching a documentary on Easter Island and booking a holiday trip to it one year later.

Of course, some of these links will be more essential than others. Without a TV and without electricity, you cannot use the TV. Without the sofa or programme guide, you can, although it is less convenient. The point is, however, that these relationships are present to some extent. We can just record the number of TV hours being watched in one year, and the number of TV programme guides being produced in one year, and calculate the (fractional) number of programme guides per hour of TV watching. This number can be used as a typical coefficient, in establishing the apparent recipe of one hour TV watching: so many TVs, so many programme guides, so many studios. This recipe is definitely not a technological recipe; it is a phenomenological recipe that is the result of the combination and interaction of technological, behavioural, economic and legislative mechanisms.

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

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

It should be stressed that these four types of mechanisms are not exhaustive, and neither is it perfectly clear which mechanisms is responsible or dominates in a certain case. That using a TV will eventually lead to waste treatment can be seen as a technological mechanism, but also as

[20] Ultimately, of course, someone pays for the production of the "free" magazines and for the treatment of the "free" garbage. There still is no free lunch, even after Friedman's death. But these items are free in the sense that there is no monetary transaction between supplier and receiver, in neither direction.
[21] Notice that the term 'causal' may be considered to be not fully appropriate in the present context. Normally, we mean by a causal relation between A and B in the sense that A causes B that A precedes B. In that sense, using a TV cannot cause the production of electricity. But producing electricity cannot be the cause of the use of the TV either. We should understand the term here in the sense of a *conditio sine qua non*.
[22] Again, we have to moderate the meaning of the term 'cause'. Waste treatment of a broken TV is not a *conditio sine qua non* for the use of a TV. It is not possible to watch a TV which has not been produced, but it is entirely possible to watch a TV which will never be treated after its end of life.

legislative one. Figure 5.8 illustrates a system dynamics model where technological and legislative mechanisms have been used as links in one model.

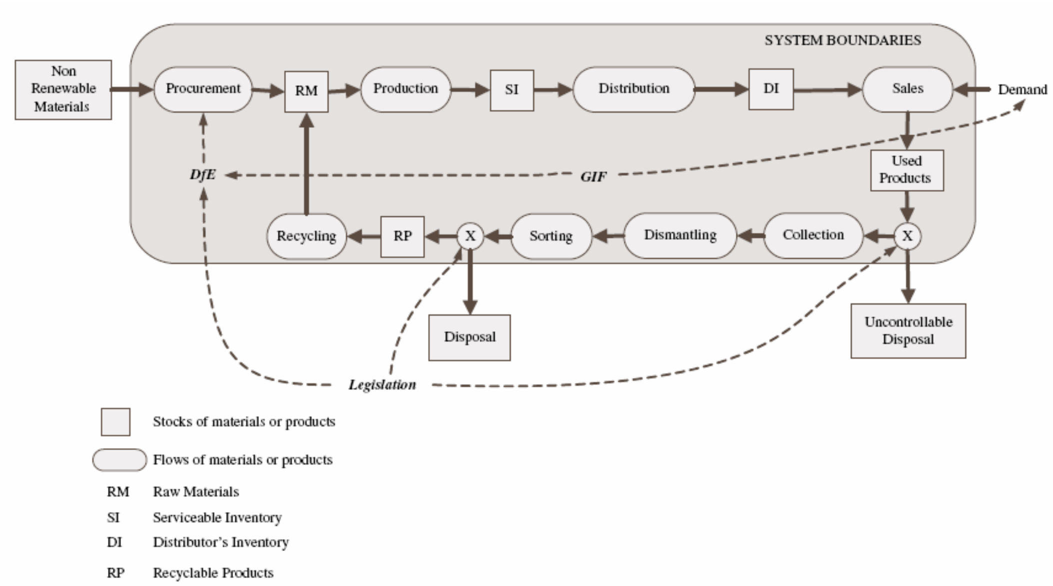


Figure 5.8: Example of a life cycle model where the connections between activities is not only influenced by physical flows of products and materials (solid arrows), but also by a symbolic link, i.e. legislation (dashed arrows). Taken from (Georgiadis & Besiou, 2008); DfE refers to design for environment, and GIF for green image factor.

In ISO-LCA, the first and the third group are in general covered to quite some extent. An LCA of TVs would cover the production, use and waste phase. Not all aspects of these are treated equally, however. Most LCAs of a TV would exclude (or ignore) the broadcast issue, and the infrastructure of the electric equipment (like the wall sockets) are typically excluded as well. The second group is completely left out of LCA in most cases. Some behavioral elements, however, do show up in some LCAs. For instance, a functional unit may take care of the user's behavior with respect to the number of hours of use and the number of hours of stand-by mode. Use of the substitution method for allocating co-production processes, leading to 'avoided burdens' is also often based on assumptions of the economics of avoided production. Another behavioral mechanism that is sometimes accounted for is the rebound effect.

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

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

The marginal technologies are often identified using static models of the variable. This requires that the LCA practitioners identify for what technologies the production is constrained to a specific production volume or to a specific production growth (Weidema et al. 1999). Constraints can be physical, political, or economic. In the energy sector, physical constraints include available potential energy in rivers etc. Political constraints include, for example, bans against further expansion of hydropower or political targets regarding CO_2 emissions. Economic constraints can include the quantity of biofuel available as by-products from forestry, sawmills and pulp mills. What we consider to be the marginal production can depend heavily on what constraints we choose to regard as fixed, and it is unclear if an objective method for identifying fixed constraints can be found.

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

The sphere of influence of a decision-maker includes not only the production of upstream products. It also includes, for example, the use of the upstream processes in other life cycles, the waste management of other products, and the level of economic activity in the society (see Table 5.1). If a manufacturer takes actions to reduce her electricity consumption, the reduced electricity demand of the manufacturer will contribute to keeping the electricity price down. This may result in an increase in the electricity demand of other consumers, offsetting part of the energy savings originally made.

Table 5.1: Example of types of consequences of a decision for the effect of profitable electricity efficiency investment.

Type of consequence	*Example*	*Modelling method*
marginal production	reduced natural-gas power production	dynamic, optimising models
demand of other consumers	increased through price reduction	partial equilibrium models
economic activity	increased through money savings	general equilibrium models
technological development	increased through additional models with experience curves	innovation models
knowledge and values	increased knowledge and inspiration through good example	marketing models

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

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

Returning to Table 5.1, net energy savings and reduced electricity price means that less money is spent on electricity in the society. The money saved can be used for other activities that, most likely, use electricity as well as other energy and materials. This rebound effect also offsets part of the energy savings originally made. Impacts on economic activity can be analysed using general equilibrium models that describe the connection between capital, labour and resources in the economy (Ibenholt, 2002).

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

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

It is apparent that a more accurate modelling of the consequences of decisions requires a series of economic models and concepts to be integrated into the models for environmental systems analysis (Ekvall 2003). The life cycle inventory modelling has, in principle, a clear target in this case: to include all processes, within and outside the life cycle, to the extent that they are affected by a decision or a decision-maker. However, the future is inherently uncertain and a CLCA practitioner can, in practice, only aim at describing the foreseeable consequences. The CLCA practitioner needs to decide what type of causal chains can be foreseen (cf. Table 5.1). She also needs to decide how far each causal chain should be traced. When the uncertainties grow too large, further expansion of the system investigated yields no additional knowledge.

A complication in terminology is that the aim to describe consequences of a decision might result in a methodology where the cradle-to-grave-perspective looses much of its relevance. Actions taken to reduce electricity demand at manufacturing does not necessarily have a discernible effect on the extraction of natural gas, the cradle of the marginal electricity in this case. The aim to describe consequences might also result in a methodology where the functional unit is no longer relevant, because the decision can affect the functional output of the system. The increased use of electricity by other consumers in Table 5.1, and the possible increase in polymer production, can generate additional functions. The rebound effects described by general equilibrium models also mean that the functional output of the economy is affected. The fact that a consequential study does not always describe alternative ways to deliver an equivalent function makes it fundamentally different from traditional LCA. It is not obvious that a study without cradle-to-grave-perspective and/or a fixed function measured in functional units should be called an LCA at all.

5.3.2 Mechanisms as a connecting link between an activity and the target variables

In the previous section, we stated that a mechanism is in the first place a causal relationship that connects the level of two activities. In this section, we will discuss the second place where mechanisms show up, connecting an activity with an issue of concern, such as the environment. Activity levels (intensities) played a central role in the first discussion. But activity levels are not interesting as such. They are an important intermediate variable, and are used in establishing the link with the indicators in the environmental, economic and social domain.

We first consider the environmental domain, which is central in ISO-LCA. The activity level of a certain activity, say, electricity production, is related to a certain set of emissions to the environment. Emission levels of carbon dioxide, nitrous oxides, etc. are associated with the output level of the electric power plant. More electricity means more CO_2. In ISO-LCA, the basic assumption of a linear homogeneous relationship is made: a double electricity production means a double CO_2 emission, no electricity production means no CO_2 emission. This is the end of the LCI and the start of the LCIA in ISO-LCA. The LCIA follows the environmental mechanism, that starts with emission, and that proceeds through a number of steps (such as increase of CO_2 concentration, change of radiative forcing, temperature change, sea level rise, loss of productive land, loss of agriculture yield, famine, mortality) to a target variable, such as human health. Like for the mechanisms that connect the levels of activities, these are causal links. For instance, an increase of CO_2 concentration leads to a change in radiative forcing. But unlike those, these mechanisms do not primarily connect the levels of activities, but embody the propagation of consequences from step to step, from driver to pressure, from pressure to state, and from state to impact. Only in the last part of the DPSIR framework, in going from impact to response, activity levels may be involved again. Examples of such responses are the increase of environmental taxes, leading to changes in purchase behavior and hence to changes in production, the construction of mitigating measures, such as the building of dikes to prevent flooding, again affecting industrial activity, or the increased demand for medical treatment after famine. Figure 5.9 illustrates this second type of causal mechanisms.

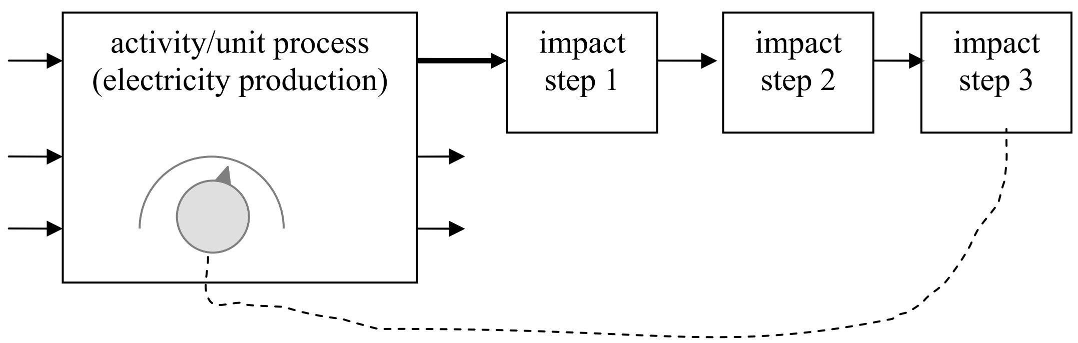


Figure 5.9: Illustration of the causal connection between the activity level of an activity (unit process). A physical flow from the activity (such as CO_2) leads to a first order impact (radiative forcing), which leads to a second order impact (temperature change), which leads to a third impact

(damage to human health). The dashed line indicates a possible causal link that affects an activity level, as a response to the impacts observed or predicted.

This second series of causal mechanisms represents – like the first series – a chain. However, it is a different chain. The first chain of Section 5.3.1 represents the life cycle of the system, while the second chain of the present section represents the impact chain. In the language of ISO-LCA, the first chain represents the inventory analysis, while the second chain represents the impact assessment. The boundary between these two is, however, not so clear as ISO-LCA suggests. Due to the societal response, impacts affect activity levels, and thus the impact chain becomes connected to the life cycle chain. The strict separation between LCI, focussing on the chain of activities, and LCIA, focussing on the chain of impacts, can this not be maintained in New-LCA.

5.3.3 A catalogue of mechanisms and models thereof

Ishikawa & Huppes (2007) abandoned the distinction between LCI and LCIA. They just distinguish seven types of mechanisms, some of which are part of ISO-LCA, and some of which could be part of a deeper analysis, i.e., of New-LCA. The seven types of mechanisms are:

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

Below, in the next few sections, we will discuss these in some detail.

ISO-LCA typically takes into account technological relations only for the inventory analysis, and environmental mechanisms for the characterization. There is, however, a long tradition of including more mechanisms into LCA. For instance, the substitution method for co-product allocation is based on the idea that some economic activities will shrink their activity level when their product is replaced by the co-product. The integration of these other mechanisms is an important way of deepening LCA; see Figure 5.10. Broadening LCA can take place at each of the indicated places, by adding economic impacts, social impacts, or environmental impacts that are not covered by present-day LCA.

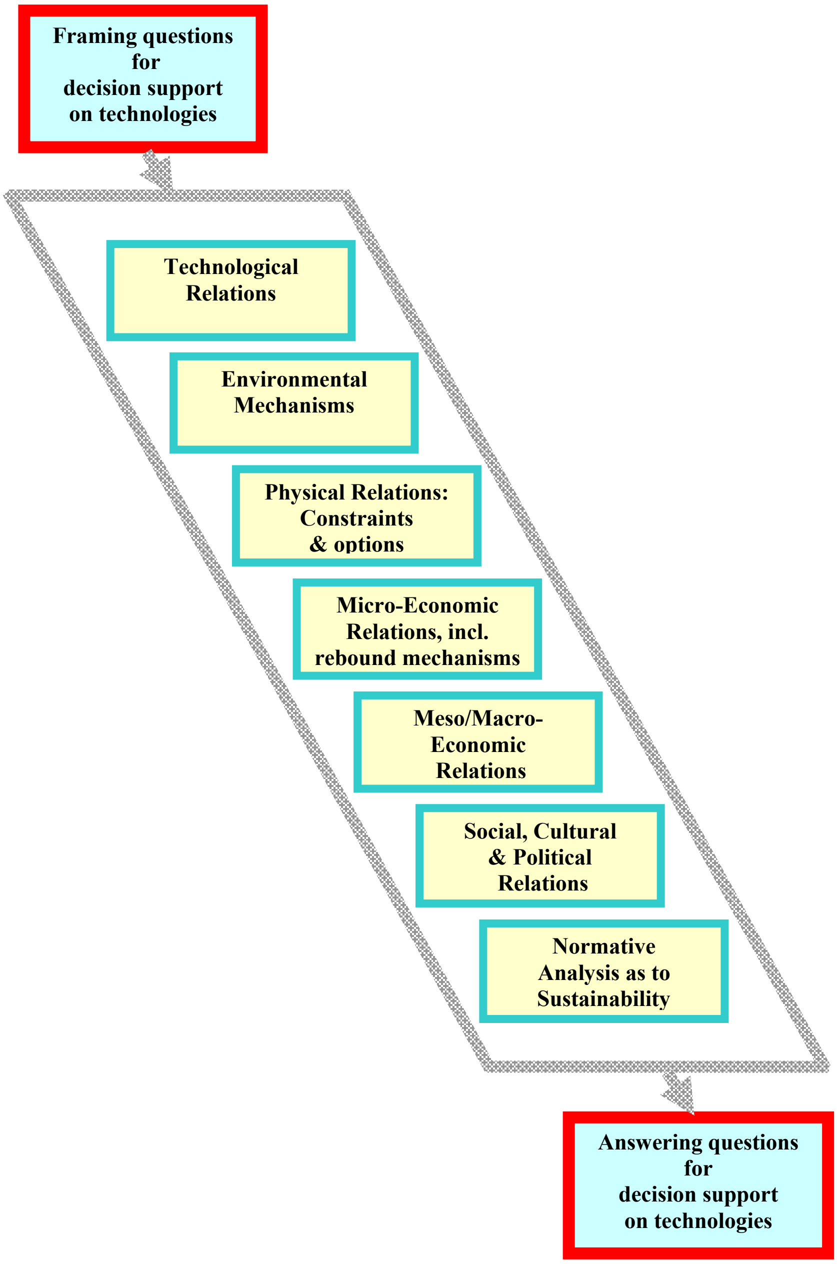


Figure 5.10: Deepening sustainability analysis of technology systems. Adapted from Huppes & Ishikawa (2007).

However, after some reflection, we have in CALCAS arrived at the conclusion that it is useful to make a distinction in two overall categories of domains:

- of empirical knowledge, e.g., on technologies, behavior, and demography;
- of normative positions, e.g., on biodiversity, income distribution, and child labor.

Disentangling Figure 5.10, we find that the normative analysis is of an entirely different nature, as it is not about empirical knowledge of what is, but about normative positions of what ought to be. The need for disentangling *is* from *ought* goes back to David Hume's *Treatise of human nature*, and is related to the distinction between positive and normative science (see Sections 2.4 and 3.6).

Another disadvantage of Figure 5.10 is that it suggests a hierarchy of mechanisms, and that the integrative aspect is not made explicit. The transdisciplinary integration is in fact the most challenging part of integrated models, such as LCA. It is the art of combining factual knowledge of economic, environmental, social and other aspects with one another, and integrating them with the ethical and societal values on economic, environmental, social and other aspects. Figure 5.11 shows the result of the redrafting of Figure 5.10, separating the empirical knowledge (the “facts”), the normative positions (the “values”) and the transdisciplinary integration (LCA, integrated models, etc.).

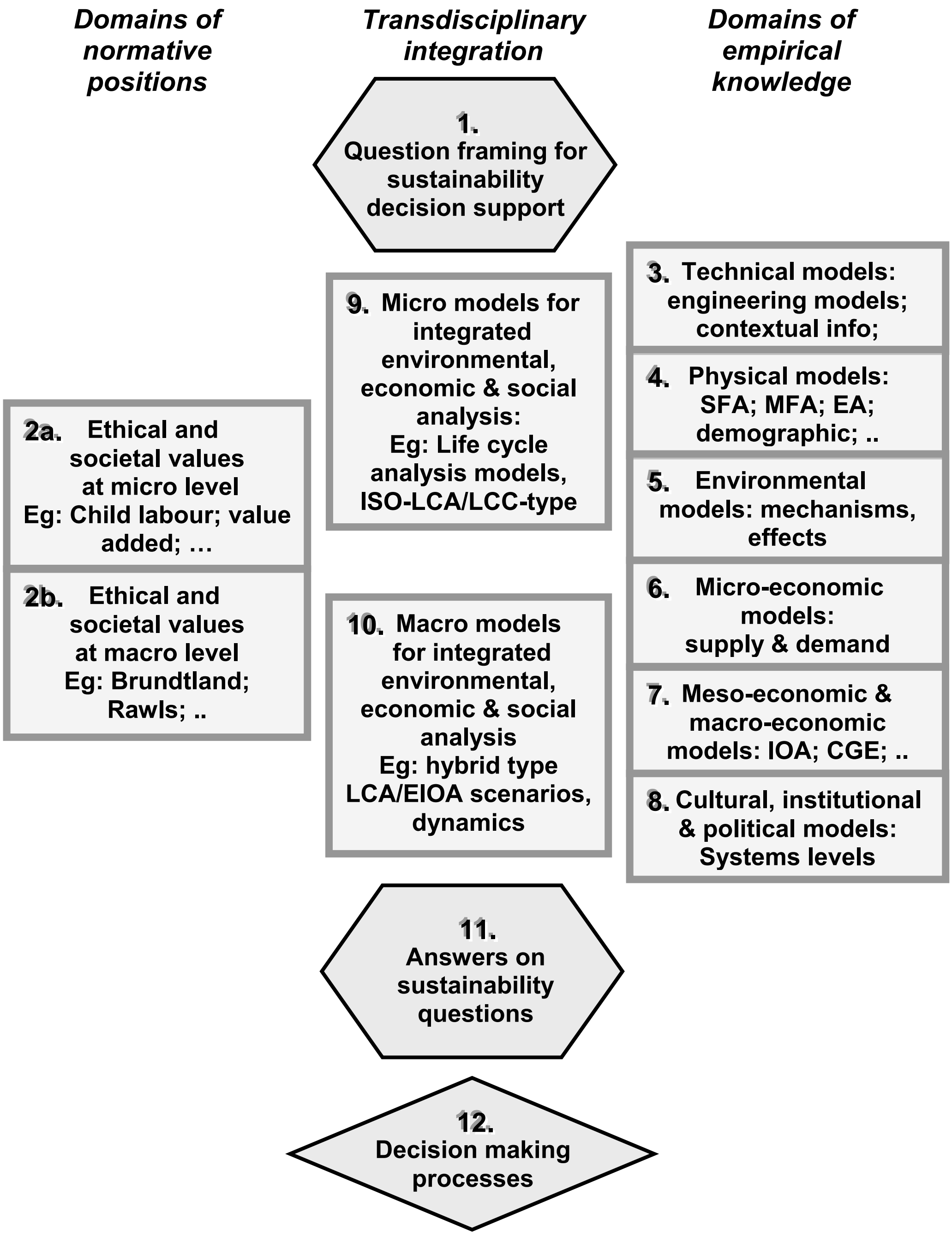


Figure 5.11: Redrafting of Figure 5.10, with a separate role for the empirical and the normative elements, and with an explicit integrative role for the tool. Adapted from Huppes & Ishikawa (2009).

In the next few subsection, the role and possible content of the different elements in Figure 5.11 will be discussed in the form of the models that can address such mechanisms.

5.3.4 Technical models

Technical models describe the principal causal[23] relationships that connect the level of two economic activities. Obviously, the economic activity of watching TV is connected to the economic activity of producing electricity. The arena of relations is much wider, obviously. Using a TV also 'causes' the prior production of the TV, and it likewise will yield a broken TV after a couple of years, causing[24] the need of waste treatment activities. Associated with the use of a TV is a whole series of broadcasting activities, requiring studios, electricity, costumes, and so on. In principle, these are also relations that can be incorporated by technical models as a *conditio sine qua non*, and they should be taken into account in an LCA.

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

5.3.5 Physical models

In getting a view on the constraints and potential of a technology system, there are physical relations which cannot be ignored. There are clear boundaries at a substance/materials level analyzed by SFA and MFA, and in terms of energy analysis, energy in a physical sense, as thermodynamic analysis. And there are limits in a physical sense as involved in land use, based on the limitations of the earth in a different way again. These limitations can be analyzed. They feed back into the micro-economic analysis. Supplying soot filters to all cars in the world is not possible within a decade due to limitations in platinum supply, as can be analyzed in dynamic SFA of platinum, reckoning with basics in supply, with other applications, and with options for recycling. This domain of physical relations is developing in terms of methods and data but as yet is not well linked to sustainability analysis of technologies. The analysis can show constraints but may also show options, where constraints are small or absent.

In ISO-LCA, such physical constraints are not taken into account at present. Outside traditional LCA, such constraints have been addressed by authors from various sides (Cleveland & Ruth, 1997; Kåberger & Månsson, 2001; Henrik et al, 2006)

5.3.6 Environmental models

Chemicals that are released to the environment from a factory leave the technological domain, and enter the environmental domain. They move from air to the soil, from the soil to the water, from the water to the sea, etc. They degrade by aerobic, anaerobic, photolytic and other mechanisms, and the decay products may be subject to new movement and degradation processes. They enter organisms where they can have a toxic effect. Some of these organisms (e.g., crops, cattle, fish) may be consumed by man. All pathways and conversions can be summarized as the environmental mechanisms. So far, the example is on toxics, but the same holds for greenhouse gases, ozone depleting substances, and so on. The relevant mechanisms have been modeled by scientists with specific domain knowledge. Their results can be incorporated into LCA models. The same

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

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

mechanisms in principle also include resource-oriented issues. Fish taken from the sea by fishery activities is not gone: the population replenishes, at least when the amount extracted is not too excessive. Issues of population dynamics are part of the science of ecologists, and can be regarded as the mirror reflection of the fate of chemicals.

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

5.3.7 Micro-economic models

Technologies function in a micro-market with direct and indirect relations to other markets. If we start producing bioethanol, we add a new energy product to the market, with price changes induced and volume changes following. These market mechanisms in principle are linked. More corn for bioethanol squeezes out corn for food and also land use for wheat production. Both prices will increase, with still other products being squeezed out and rising in price in turn. These market mechanisms are interrelated. Combining a limited number of markets is possible, as in partial equilibrium modeling. Due to the interrelatedness, there is a steep limit to the number of markets that can be taken into account simultaneously, a few dozens at most. This means that a fully described technology system cannot be linked to an integrated market model. On the other hand, knowing how key markets function is essential in assessing the sustainability of technologies, as the biofuel example has shown. The lack of reliable modeling in this respects has lead to unintended disaster. Micro-economic market relations cannot be left out of account, but how to take them into account adequately and with the right priorities constitutes a fundamental research question for integration.

Standard ISO-LCA does not take into account micro-economic relations. However, a number of proposals and case studies have been published in which some micro-economic aspects are part of the analysis. For instance, Weidema (2000) and Ekvall & Weidema (2004) include shifts in market structure as part of the LCA inventory. Likewise, Hofstetter et al. (2006) and Thiesen et al. (2008) discuss the inclusion of rebound-effects.

5.3.8 Meso- and macro-economic models

The next level of embedding places technology systems in their macro-economic context. Expanding one group of processes and technologies, with increasing resource inputs not only from nature, but also in terms of labour and capital. Technological improvements imply productivity rises, with more output for less inputs of labour and capital. The economic growth resulting, as increase in factor productivity, implies increased spending or increased leisure, or a combination of both. Macro-economic relations form a key element in sustainability analysis. The link at a meso and macro level between economic activities and their environmental impacts is developing, though surely not yet to maturity. If adequately developed, and linked to the technology and market level, and taking into account physical constraints, the macro-economic level could catch the links between technologies and environment and could incorporate major social aspects as on labour quality and income distribution.

Inclusion of economic effects beyond the micro level is definitely beyond what is mentioned in ISO-LCA, and also what is done in typical LCA-studies nowadays.

5.3.9 Cultural, institutional and political models

At the side of societal mechanisms, there is the broader set of mechanisms that can be referred to as socio-cultural, institutional and political relations. Technologies may not be accepted or only slowly, like nuclear technologies and genetically modified organisms. Or they may be prevented from coming to maturity, due to restrictions on patent rights, as seem to be the case with fundamental redesign of heavy industries as patents will have expired before they can become profitable. Or negative effects may be counteracted by public policies, as in safeguarding nature areas by zoning laws, which could reduce the most severe negative effects of biofuels.

Relations like these are not part of present-day LCA. They may be difficult to incorporate in the modelling framework anyhow. A typical place for this may be the stakeholder involvement around goal and scope definition and interpretation of ISO-LCA.

5.3.10 Ethical and societal values

The analysis for sustainability decision support ultimately is to be guided by explicit sustainability criteria. There is a vast literature in this domain, which requires a transformation in order to be used for normative analysis on sustainability in this specific context of application.

The most important normative element in present-day LCA studies is weighting. Weights are sometimes derived from panel discussions or interviews, and sometimes from policy documents or monetary principles. There is, however, much more to say on this (for instance: what are the issues of concern? is resource depletion an environmental issue or an economic issue? is societal time preference compatible with transgenerational sustainability?), and also the place of this element (as part of the model, as an interactive multi-criteria based activity within the LCA-framework, or as an interactive discourse with stakeholders).

5.3.11 Models for integrated environmental, economic & social analysis

This is the pace where we in fact find LCA, along with similar models, as an integrative framework. LCA as such does not address technical relationships, nor environmental dose-response characteristics, nor economic mechanisms. It only offers a carefully designed place for the integration of the disciplinary knowledge from these fields. Likewise, it offers a place to bring in normative positions in a clear and transparent way, but the normative positions themselves are not in any sense part of LCA.

5.3.12 The ISO-framework revisited

Starting with the overview of mechanisms in Figure 5.11, we are now ready to present a revision of the ISO-framework for LCA. In this framework for New-LCA, we have tried to stick to the classic ISO-framework whenever possible. Thus we have established the following correspondences (see Figure 5.11):

- question framing for sustainability decision support ⇔ Goal and scope definition
- technical models, physical models, environmental models, micro-economic models, meso/macro-economic models, cultural, institutional and political models, ethical and societal values ⇔ Modelling ⇔ Inventory analysis & Impact assessment
- answers on sustainability questions ⇔ Interpretation

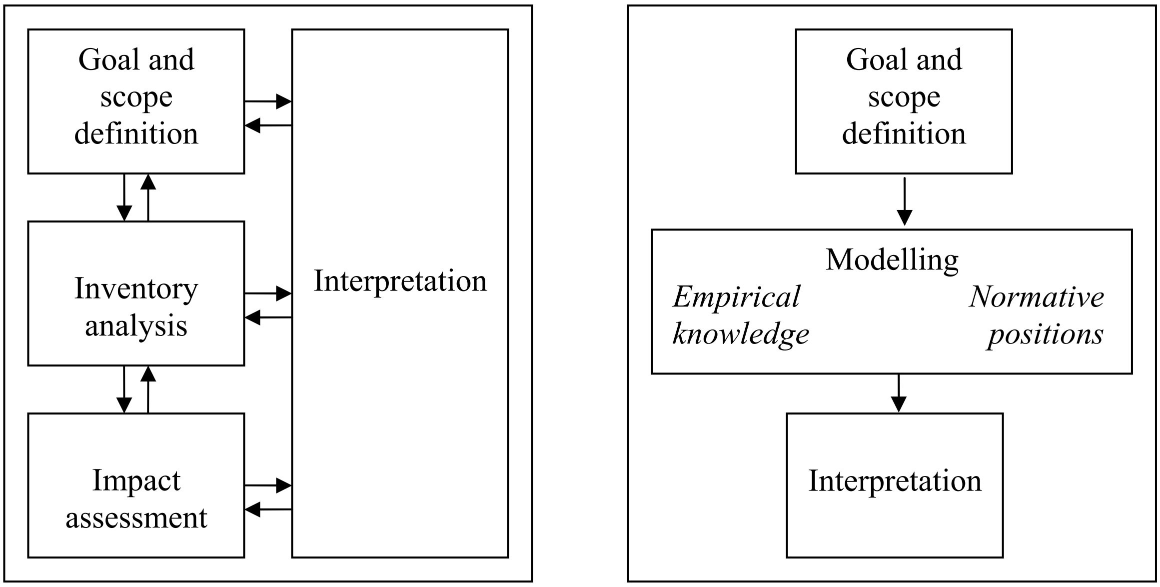


Figure 5.12: The ISO-framework (left) and the proposed framework for New-LCA (right). The solid arrows indicate the major information flows only.

The two most striking thing about this framework for New-LCA are:

- it is very similar to the old framework for ISO-LCA;
- inventory analysis and impact assessment have merged into one modelling step.

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

The second issue is more intricate. As shown in Figure 5.10, and as has become clear during the last decade of academic work on agricultural production, climate change, impacts of land use, rebound and so on, it is difficult to make a clear separation between behaviour and technology on the one hand, and between technosphere and ecosphere on the other hand. One example suffice to reinforce this. The fuel needed to drive one km with a certain car depends on technology, drive style, other traffic, traffic policy. So a seemingly technological parameter to specify a unit process depends on the entire complex mentioned (technological relations, environmental mechanisms, physical relations, micro-economic relations, meso/macro-economic relations, social, cultural and political relations, normative analysis as to sustainability). A reductionist separation of this complex into a technosphere and an ecosphere appears rather shallow.

5.4 Environmental, economic and social LCA: mechanism, metric, and indicator

As discussed in Section 2.2, a sustainability analysis is supposed to cover at least three main dimensions of concern: people, planet and prosperity, or social, environmental and economic. There has been quite some confusion in the literature on the question which of theses domains is addressed by a certain tool. For instance, input-output analysis (IOA) is said to address economic issues, whereas environmental input-output analysis (EIOA or EnvIOA) is said to address environmental issues. This suggests that the two tools have a different set-up and require different input information. This is, however, not the real case. Generally speaking, EIOA requires additional information to IOA, not different information. In this section, we will try to disentangle this confusion.

In an IOA, the causal links between the activities are described by technological coefficients. These coefficients are derived from observed transactions of physical products (say, in kg) or of monetary payments (say, in euro). In a review article by Leontief (1986), the first two tables show these two cases (p.2340: Table 1 with items such as “100 bushels of wheat” and Table 2 containing the corresponding 200 $ of agricultural output. Leontief remarks that “in principle the intersectoral flows ... can be thought of as being measured in physical units, in practice most inputs-output tables are constructed in value terms” (p.2340) and that “the structural matrices are usually computed from input-output tables described in value terms” (p.2341). Thus, the basic structure of an IOA, whether an economic IOA or an environmental IOA, can be written down in monetary terms or in physical terms. The take home message is that this core part of an IOA is neither economic nor physical, but is merely a reflection of the apparent recipes of producing industrial outputs. We can do this internal accounting and model construction with monetary information (thus obtaining a monetary input-output table, a MIOT) or with physical information (using a physical IOT, a PIOT). Under certain assumptions, “the two models are equivalent except for the change of unit operation” (Weisz & Duchin, 2006, p.540).

Despite the fact that the structure of the causal links in IOA and EIOA are the same, they do address different indicators. For instance, in an IOA, one calculates the sectoral outputs as a result *per se*, while it is only an intermediate result in an EIOA. In IOA, one is also usually interested in changes in the items that are known as the “value added”, such as labour, taxes, and profit. In EIOA, these items are often ignored or left out, and other items are added as satellite accounts, such as emissions to the environment, natural resource extractions, or energy use. These naturally are recorded in physical units, such as kg of pollutant or MJ of energy. But they can in a welfare-theoretic context be accounted in monetary terms as well, thus representing the external costs of production and consumption.

In conclusion:

- IOA and EIOA have the same or an equivalent accounting and modelling structure for the interindustry part, that is for modelling the causal mechanisms that link the activity levels of industries;
- IOA and EIOA have different satellite accounts that contain the information that is needed to address different indicators: economic (employment, profit, etc.) vs. environmental (emissions, resources, etc.).

The purpose of this section is, however, not to compare IOA and EIOA. Rather, it focuses on the relation between the models for environmental LCA and forms of LCA that have a different scope, such as life cycle costing (LCC) and social life cycle assessment (SLCA). Klöpffer (2008, p.90) suggest in a conceptual formula that a life cycle sustainability assessment (LCSA) is an LCA, an LCC and an SLCA, done in a consecutive way:

$$LCSA = LCA + LCC + SLCA$$

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

- LCA, LCC and SLCA have the same or an equivalent accounting and modelling structure for the interindustry part, that is for modelling the causal mechanisms that link the activity levels of industries;

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

Considered in this way, LCA, LCC and SLCA can be seen as three ways of looking at the same system. This resembles the cover of Douglas Hofstadter's book *Gödel, Escher, Bach* (1979), reproduced in Figure 5.13.

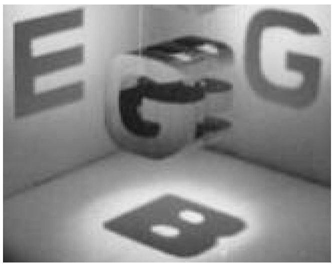


Figure 5.13: Fragment of the cover of Hofstadter's *Gödel, Escher, Bach*, which demonstrates how a certain object reveals different features when projected from different sides. A similar thing can be envisaged for the projection of the technological system on the environmental, the economic, and the social sides. (Picture adapted from http://en.wikipedia.org/wiki/G%C3%B6del,_Escher,_Bach).

In the present case, we have a technological system that displays environmental, economic and social indicators when projected from different sides. Altogether, we should conceive the exercise to be carried out as the modelling of one single technological system, containing the life cycle of the product under study, and the adding of satellite information on environmental, economic and social data of the different unit processes in the technological system; see Figure 5.14.

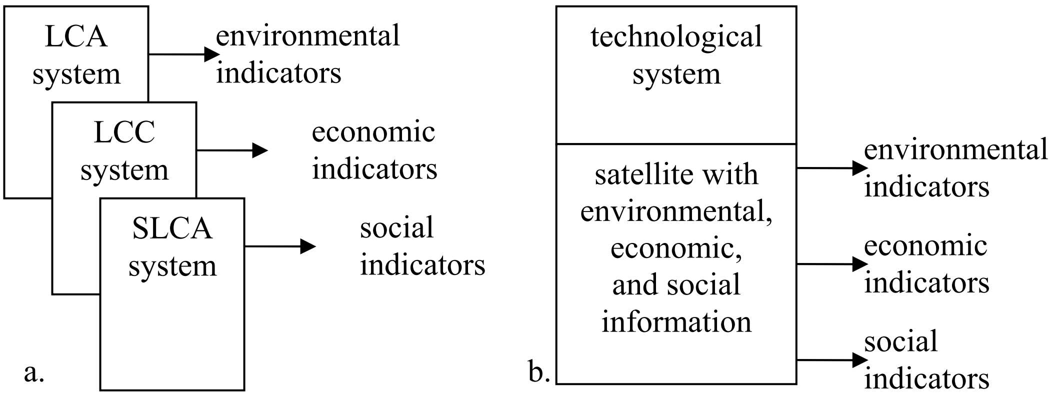


Figure 5.14: Redesign of environmental analysis (LCA), economic analysis (LCC), and social analysis (SLCA) as the sum of three separate analyses (a) into one analysis with three different sets of indicators (b).

Redrafting the equation in which LCSA is conceived as the sum of a separate LCA, LCC and SLCA, we can now expand the previously obtained

$$\mathbf{i}_{env} = \mathbf{T}_{env}\mathbf{T}_{tech}^{-1}\mathbf{f}$$

with two similar equations, for the LCC

$$\mathbf{i}_{econ} = \mathbf{T}_{econ}\mathbf{T}_{tech}^{-1}\mathbf{f}$$

with $\mathbf{T}_{econ}$ the satellite matrix of cost information, and for the SLCA

$$\mathbf{i}_{soc} = \mathbf{T}_{soc}\mathbf{T}_{tech}^{-1}\mathbf{f}$$

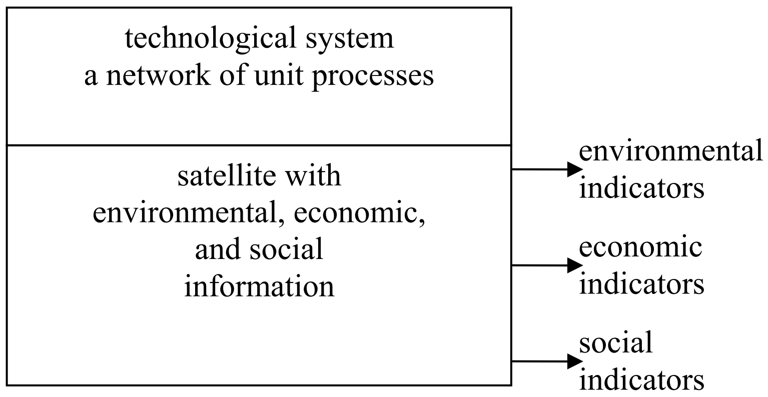
with $\mathbf{T}_{soc}$ the satellite matrix of social information. The central point of this is that these three equations share the same $\mathbf{T}_{tech}$, the matrix that represents the structure of the technological system. In a combined form, we get

$$\mathbf{i} = \begin{pmatrix} \mathbf{i}_{env} \\ \hline \mathbf{i}_{soc} \\ \hline \mathbf{i}_{econ} \end{pmatrix} = \begin{pmatrix} \mathbf{T}_{env} \\ \hline \mathbf{T}_{soc} \\ \hline \mathbf{T}_{econ} \end{pmatrix} \mathbf{T}_{tech}^{-1}\mathbf{f}$$

and we can conclude that

$$effort(LCSA) \ll effort(LCA) + effort(LCC) + effort(SLCA)$$

Apart from reducing the effort of using the proposed framework, there is another advantage: it is much easier to safeguard the consistency between the LCA, LCC and SLCA with respect to system boundaries and other choices when the technology matrix $\mathbf{T}_{tech}$ is shared.



5.5 Asking and answering questions

In Figure 5.10, we see that the modeling activity itself is surrounded by two other activities:

- question framing for sustainability decision support;
- answers on sustainability questions.

These two activities connect the real-world problem to the abstracted modeling exercise. Their role is comparable to that of the goal and scope definition and the interpretation of the ISO-LCA framework.

In this section, we will briefly discuss these two activities. At the outset, it must be clear that these two activities are of a different nature than the modelling exercise itself. Ancient philosophers distinguished the Good, the True, and the Beautiful: Verum, Bonum, Pulchrum. LCA does not touch issues of aesthetics through the beauty, but it definitely combines considerations on truth and goodness. A "true" model of something useless has no value, and neither has a model of something that is "good" any meaning when the analysis is false. The modelling exercise is supposed to bring in the truth, and the framing and answering steps are supposed to address the issue of goodness.

5.5.1 Question framing for sustainability decision support

Framing question amounts to a number of things. In the first place, the question is posed in a clear way. For more than 20 years, the LCA world knows that this is important. One cannot simply ask: What is better, a bottle of soft drink or a can of soft drink? Such a question is ill-posed. The Goal and scope definition phase has been introduced into the LCA framework in order to help to pose the question in a more clear and unambiguous way. Elements of clarification include:

- the function that the alternatives are supposed to fulfill;
- the alternatives selected to be compared;
- the context for which the analysis is valid (e.g., the geographical, temporal and technological scope);

- the intended application of the LCA-study (e.g., company-internal optimization, public choice, etc.).

However, developments since the drafting of the ISO-standards have made clear that framing involves more. ISO-LCA, for instance is functional-unit based. It is assumed that the LCA-practitioner sets a functional unit, say 1000 hours of TV-watching, and then analyzes several product alternatives that are capable of fulfilling that function. Things are not always that easy. In a comparison of light bulbs, one might select the functional unit lighting a room for 1000 hours with light of a certain quality. We know, however, that people tend to switch off incandescent light bulbs more frequently when they leave the room for a while than when they use a fluorescent light bulb. This is one example of a behavioral aspect that could be included in an LCA. Moreover, as the cost of using a light bulb decreases, people tend to use them more often. Thus, we see gardens which are populated with many "energy-efficient" lights. This is one example of a so-called rebound effect, and some LCA-scientists have been active in incorporating it into LCA-studies. But there are many more examples. LCA is being used to analyze different societal scenarios, with different technologies and with different consumption patterns. LCA-studies of waste treatment incorporate aspects of future demand of co-generated electricity or recycled materials.

In general, we think the functional-unit based ISO-LCA should be seen as a special case of a more general New-LCA set, which is not necessarily functional-unit based. The IPAT-structure (Section 5.1.2) alludes to that: in ISO-LCA P and A are constant, in New-LCA we may allow for changes in P, in A or in both.

There are two principal ways of including behavioral, economic and other mechanisms in New-LCA:

- as part of the inventory model, i.e. by specifying unit process data in which the coefficients reflect technical, economic, behavioral and other mechanisms;
- as part of the goal and scope definition, by specifying alternative scenarios that fulfill different functions instead of alternative products that fulfill an identical function.

In the first solution, we have endogenized the mechanisms in the form of coefficients and functional relationships; in the second solution, they are part of the practitioner-imposed question. Where to put them depends on the situation. Some behavioral aspects may well be part of the inventory modeling. But in many studies, the choice of scenarios is a crucial element of specifying the context of the entire analysis. In such cases, these behavioral aspects should not be hidden in an otherwise technical annex with thousands of numbers. Rather, they should be explicitly discussed at the outset of the study. Section 5.7.2 discusses the incorporation of scenarios as part of the goal and scope definition.

5.5.2 Answers on sustainability questions

In a decision-support tool, answering questions means translating the available information into one or more conclusions and recommendations. In ISO-LCA, examples are a preference order ("product A is preferred to product B") and recommendations for improvement ("reducing emission 1 from process 2 will reduce the burden considerably"). In ISO-LCA, the interpretation phase is reserved to this conversion step. Although ISO-LCA devotes many words to considerations on uncertainty and data quality, it is not clear where and how such information is processed. At some places, it seems to be suggested that the inventory analysis and impact assessment deal with the uncertainties, while at other places the interpretation seems to be the right place. Moreover, as ISO-LCA discommends the use of single indicators and weighting, the question how multiple conflicting results must be combined to arrive at conclusions and recommendations is unclear. This unclear status of life cycle interpretation is reflected in many ways. In 12 year volumes of the International Journal of Life Cycle Assessment, there are just six papers which have the word "interpretation" in its title as a keyword, whereas the term “inventory” gives about 100 hits. Considering that SETAC’s Code of Practice wrote in 1993 that the inventory analysis was “Defined and understood” (Consoli et al., 1993, p.7) and that it “needs some further work” (ibid.), while the interpretation wasn’t even there at that time, this is amazing. It simply means that the inventory analysis has been subject to further scientific development, while the interpretation, the least elaborated phase that most needed scrutiny, has escaped the notice of most scientists. Another sign of lack of attention for interpretation is the fact that many journal articles describing case studies have a section on Goal and scope, one on Inventory, one on Impact assessment, but not one on Interpretation.

The idea of an interpretation phase, we think, should be a highly interactive process, using information of the previous phases, adding other information (e.g., from previous LCA-studies, from other types of sustainability analysis, or comments and suggestions from expert reviewers or stakeholders), using statistical techniques (such as Monte Carlo analysis and hypothesis tests), using decision-analytical techniques (such as the analytic hierarchy process and concordance analysis). This plethora of approaches can be used to help to formulate a nuanced answer to the question that was formulated at the beginning of the LCA-study.

5.6 A comparison between the ISO-LCA-framework and the new-LCA-framework

Figure 5.12 shows the two frameworks next to one another. As discussed in Section 5.3.12, one of the most striking things is the merging of the inventory analysis and impact assessment phases into one modelling phase (see Figure 5.15). This is done for two reasons:

- The simple one-way causal relationship from economic activity to environmental impact is no longer sufficient in New-LCA. Rather, as the DPSIR framework (Figure 5.3) illustrates, there are causal connections the other way around as well, between environmental impact and economic activity.
- The term “inventory” in the framework of ISO-LCA neglects the modelling aspect, in fact by putting emphasis on the data aspect, the model itself was implicit and the only real action is calibration of the coefficients of the technology matrix ($\mathbf{T}_{tech}$ or **A**) and the environmental matrix ($\mathbf{T}_{env}$ or **B**). Inventory analysis implies at least as much modelling as impact assessment (in fact, even more).

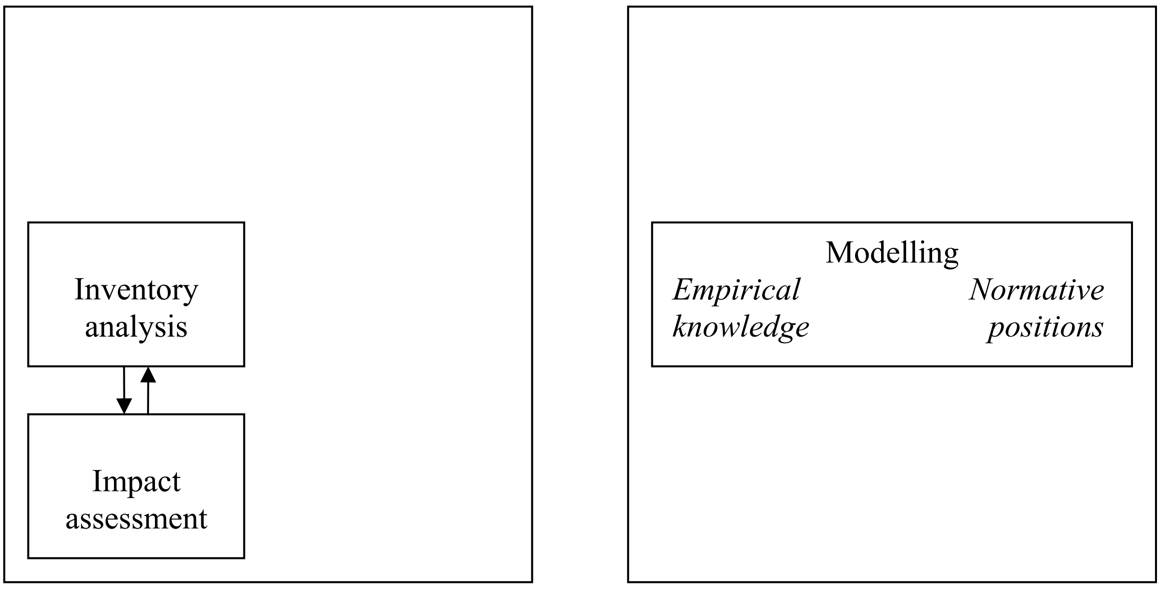


Figure 5.15: Inventory analysis and Impact assessment of ISO-LCA merged into the modelling phase of New-LCA.

Nevertheless, there is of course a clear separation of content within the modelling phase:

- modelling the technological system: this roughly comprises the old aspects system boundary, flow diagram, data collection, allocation and calculation;
- modelling the environmental, economic and social pathways: this comprises the old aspects of defining impact categories, characterization, but also data collection for these satellite data;
- constructing the environmental, economic and social indicators: this includes calculation steps, and may also contain the traditional optional aspects like normalization and weighting.

The changes for Goal and scope definition and Interpretation are much smaller. Of course, with the broadening and deepening, additional aspects can be addressed in these phases, and some other refinements of the framework have been introduced. But the main idea stays the same:

- goal and scope definition for framing questions for decision support on technologies;
- interpretation for answering questions for decision support on technologies.

This concludes the overview of the general idea. The next section discusses how specific topics of attention in recent LCA development have been brought into the new framework. Furthermore, Chapter 6 discusses in more detail the steps with the three phases of the new framework.

5.7 The place of specific elements in the new-LCA-framework

Scientific developments around LCA have been everywhere. Examples include:

- the distinction of consequential and attributional LCA and prospective and retrospective LCA;
- the incorporation of scenarios into LCA;
- issues of time and space (the possibility of dynamic LCA, spatially differentiated LCA and/or LCIA);
- the use of multicriteria analysis in LCA;
- the use of valuation methods.

This section will address where such elements can be incorporated in the new framework for LCA.

5.7.1 Consequential and attributional LCA; prospective and retrospective LCA

In the literature on LCA of the last decade, some nagging and interwoven issues have been discussed. These relate to the purpose of LCA and in relation to that the basis for modelling and data. Terms that show up in this discussion are consequential, attributional, prospective, retrospective, marginal, average, change-oriented, descriptive, etc. Some of these issues are related or even identical, and whenever a relation is made, it is sometimes justified, but not always. This section tries to clarify the most important issues within the context of the framework for New-LCA.

Guinée et al. (2002) start by stating the overall purpose of LCA as "to compile and evaluate the environmental consequences of different options for fulfilling a certain function." This then leads to discerning two types of questions for LCA:

- In the first, the question of interest is the contribution of a particular way of fulfilling a certain function to the entire spectrum of environmental problems as they currently exist or are being created. Using LCA to answer this question is referred to as doing a descriptive LCA, although other terms like retrospective LCA, level 0 LCA, and status quo LCA are also encountered in the literature.

- In the second mode of interpretation the emphasis is on change. The analysis then addresses the environmental changes resulting from a change from or to a particular way of fulfilling a certain function. This change may assume a variety of forms, illustrated by 'drinking one more beer' and 'drinking a different brand of beer'. The use of LCA for answering this second type of question is referred to as doing a change-oriented LCA, or sometimes a prospective LCA, or a level 1 (or 2 or 3) LCA.

5.7.2 The incorporation of scenarios into LCA

Confusingly, the term scenario is used in two quite different ways. In some models, a scenario is the outcome. For instance, a model can predict that we will arrive at a scenario in which indistrialized civilization has disappeared. In other models, a scenario is the starting point. For instance, a model can predict what will happen under the scenario of world-wide free trade. In fact, both meanings are useful, and they can even be consistent with each other. For the scenario that is the output of model 1 may be fed as an input into model 2.

In this section, we focus on the use of scenarios as an input into New-LCA. Traditionally, LCA (at least, consequential LCA) is based on a number of assumptions:

- small changes: the functional unit is assumed to be something like 1 MJ of electricity or 100 km of transport, a quantity that is negligible compared to the annual global market;
- linearity: the extra 1 MJ of electricity is assumed to be provided by existing infrastructure, no new investments are assumed to happen as a result of it.
- ceteris paribus: some things are assumed to change, but most things are assumed not to change. For instance, in an LCA of incandescent light bulbs versus fluorescent light bulbs, no changes in behaviour is taken into account, neither has the difference in price been investigated as to consequences in budget shifts;

These assumptions have many advantages in keeping the LCA model simple and feasible. Just to mention two things: they allow for the use of implicit linear model equations, and they allow to focus the modelling of the technological system to physical mechanisms, excluding behavioural and other mechanisms that are difficult to model.

Guinée et al. (2002, p.408) distinguish within the consequential (or change-oriented) LCA three main types of decision:

- occasional choices (e.g., should I take the high speed train of the plane to my meeting in Paris next week?);
- structural choices (e.g., should I take the high speed train of the plane to my weekly meetings in Paris?);
- strategic choices (e.g., should the government invest in high speed railroad or in airports).

These three main types of decision are regarded as equally valid, but it has also been observed that they require different models:

- occasional choices require optimization models, such as linear programming models;
- structural choices require the class of models that is central in ISO-LCA;
- strategic choices require "an approach that would draw more heavily on elements of scenario analysis" (Guinée et al. (2002, p.409)).

This sets the context of the use of scenarios in LCA: when the changes are more than marginally small, many of the assumptions no longer hold:

- technologies can no longer be characterized with constant coefficients;
- capacities of technologies is no longer constant;
- the change in economic structure will affect prices and preferences, and hence induce change in life styles;

- background concentrations of pollutants will change;
- etc.

There are two principally different ways of modelling structural changes of the technological system:

- endogenously as the result of models, where the changes in technology are the outcome of models, like in Schumpeterian evolutionary economics;
- exogenously as specified by a model user, where the changes in technology are specified as the result of creative or explorative thinking.

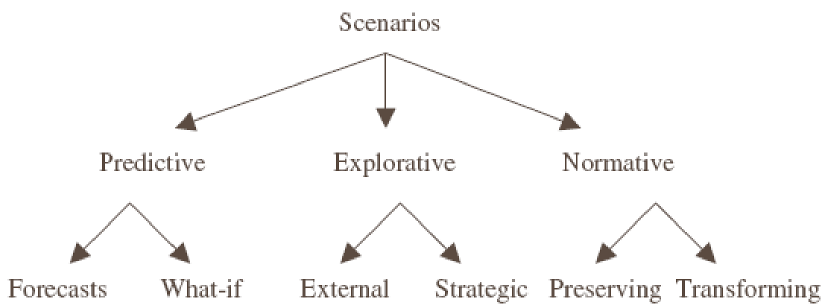


Figure 5.16: From Börjeson et al, 2006.

5.7.3 Issues of time and space

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

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

Of course, there are more issues that relate in some way to time and space. For instance, models may contain activities related to transport (displacements in space) or storage (displacement in time), with their associated impacts. These activities, however, are considered here to be part of the system that models the technological mechanisms; see Section 5.3.4.

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

- to ignore such specifications, for instance simply adding an emission of NO_x in Spring 2003 in Sicily and an emission of NO_x in July 2004 in London into an emission of NO_x at an unspecified time and an unspecified place;
- to maintain such specification, for instance keeping separate the two emissions of NO_x in the example above;
- to use such specifications for a dedicated aggregation; see below for more detail.

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

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

On the other hand, evolutionary models allow for a modelling of changes in the course of time. We can study how changes will propagate in different parts of the system as a function of time. Two variants that may be seen are models that work with discrete time steps, and models that incorporate a continuous time variable. The first of these may deliver time series, e.g., emissions in year 1, in year 2, etc. The second one may describe emissions as a continuous function of time. Terminology is sometimes confusing here. The word "dynamic" derives from the Greek word for force or power, and is in scientific use in the context of classical mechanics to indicate the results of forces (such as gravitation) that act on bodies (such as planets).[25] As forces lead to changes in time, the word "dynamic" has received a wider use, indicating anything that has to do with changes in time. Newtonian mechanics deals with (continuous) differential equations, allowing the description of systems at any time. However, the term "dynamic" has also become increasingly popular to denote changes that are measured as time series. The consequence is that what is a dynamic model to one is not so to another one.

The last decade, many researchers have developed principles of and elaborations of spatially differentiated characterisation models and factors that can be connected to a spatially differentiated inventory table. Examples can be found in Potting & Hauschild (1997), Krewitt et al. (1998), Potting et al. (1998), Potting (2000), Huijbregts et al. (2000), Moriguchi & Terazono (2000), Bare et al. (2002), Pennington et al. (2004), Basset-Mens et al. (2006), Hauschild et al. (2006) and Bellekom et al. (2006).

5.7.4 The use of multicriteria analysis in LCA

Multicriteria analysis (MCA) is a set of methods to deal with structuring choices between a number of alternatives with information on several criteria. In ISO-LCA, the criteria are in most cases a number of environmental impact categories at the midpoint level, such as climate change, toxicity and acidification. Alternatively, endpoint categories, such as human health, ecosystem quality and resources are used. Traditionally, the weighting step is included to convert scores on different impact categories into a single number, for every product alternative. Weighting, however, is a cumbersome and controversial issue.

[25] See, for instance, Leibniz' *Specimen Dynamicum* of 1695.

Several multicriteria techniques have been developed to structure a decision. Some techniques help to develop weighting factors, while other techniques can prepare a decision without explicit weighting factors, using so-called outranking methods or other techniques. The use of multicriteria techniques in LCA has been explored by several authors (e.g., Seppälä et al., 2001; Hertwich & Hammit, 2001; Geldermann & Rentz, 2005), but no generally accepted procedure has been formulated so far.

In broadening the ISO-LCA into New-LCA, more types of indicators will be taken into account, e.g., on social and economic domains. There is an extended aggregation problem within these new domains, as well as between the three domains. So, in New-LCA, the need for the development and application of multicriteria methods will be even more urgent than for ISO-LCA. MCA provides, like LCA, and integrative framework. It defines the role for empirical information, and it allows for the introduction of normative judgments. As such, New-LCA would incorporate techniques from MCA, and it would probably do so in a foundational sense. The consistency requirements of MCA pose conditions to New-LCA.

5.7.5 The use of valuation methods

One of the important ways of aggregation different environmental impacts is incidentally one of the important ways of aggregation environmental and economic indicators as well. It is represented by the approach by environmental economists in estimating the external costs due to pollution and other environmental impacts. If a chemical company pollutes a river, the fishers downstream will experience an economic damage. As long as this damage is not compensated by the chemical company, environmental economists speak of external costs, or externalities. The estimation of these externalities is referred to as the problem of valuation. Within environmental economics, many valuation techniques have been developed, some of which may be grouped into classes of techniques. Well-known terms are willingness to pay (WTP), damage costs, hedonic pricing, and revealed preference.

Valuation methods have been used extensively in certain areas of environmental analysis (see, e.g., Spadaro & Rabl, 2001; Rabl & Holland, 2008). In LCA, the most well-known use is in the EPS method (Steen, 1999). Yet, its use has been disputed as well, both in LCA (see, e.g., Hellweg et al., 2003) as well in a more general context (see, e.g., Ackerman & Heinzerling, 2004).

Despite serious problems of valuation, its use may be considered as an interesting aspect of New-LCA in at least certain contexts. The normative elements contributing to New-LCA provide the right place to incorporate it.

5.8 Combined models

Different types of models can be combined to achieve a more comprehensive analysis of the environmental, economic or social aspects of a life cycle or decision. As an example, hybrid analysis is a combination of the process LCA and environmentally extended input-output analysis.[26] However, the concept of hybrid analysis is a much broader concept (Udo de Haes et al., 2004).

There are two fundamentally different approaches to linking models. Soft linking means that the results from one model are manually fed into the other. A number of iterations can be performed were both models are manually tuned to be consistent with each other. Hard linking means that the

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

models are integrated to become, in essence, a single computer model. When a hybrid analysis is conducted with an LCA model that includes input/output tables, it is a case of hard linking.

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

A special case of soft linking is the toolbox approach (see, e.g., Wrisberg et al, 2002; Ekvall et al., 2005), where the models are deliberately kept separate to allow for a methodological flexibility. Different models are selected and soft linked depending on the need of the particular case study. The toolbox procedure relies on the recognition that different approaches are required for modelling different types of causal mechanisms (see Table 5.1), and that no single person is an expert on all approaches. For this reason a toolbox approach may require not only a combination of models but also a combination of experts.

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

Another issue in combining models is not the linking, either soft or hard, of the models where the output of one is the input of the other, but the combined consideration of their outputs. For instance, when one has a result of an environmental assessment and one of an economic assessment for a number of options (e.g., alternative products), there are at least three ways to combine these:

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

5.9 Simplified models

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

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

In inventory analysis, simplifications include the following:

- replacing the time-consuming step of data collection by using readily available general purpose databases, such as ecoinvent, at least for a substantial part of the analysis, even when these datasets are not fully representative for the question under study;
- neglecting substantial parts of the product system, e.g., leaving out all capital goods;
- using IO-based LCA (or EIOA) instead of the ISO-recommended process-based LCA[27];
- focusing on a selection of environmental flows only, e.g., only on inputs (like in MIPS), or only on greenhouse gases (like in Carbon Footprints).

In impact assessment, simplifications include the following:

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

There are many more ways of simplifying LCA.

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

LCA, on its turn, can be considered to be a simplification as well. ISO-LCA generally ignores spatial and temporal information, is based on linear modelling of technologies, and excludes many behavioural mechanisms. These are all simplifications. A question is then: of what is it a simplification? There is no generally recognized model that includes these features, and which can serve as a benchmark of ISO-LCA. In the end, every model is by definition a simplification of the real underlying phenomena. The point to be elaborated in New-LCA is that there is a need of a framework consisting of a full model, and that there are guidelines on when to switch off which elements, depending on the goal and scope of the model. While a full LCA may be needed in some cases, a carbon footprint may suffice in other cases. In other cases, a spatially differentiated LCA is absolutely essential. And there are also cases where consideration of rebound mechanisms is definitely not needed. The different modelling elements in Figure 5.11 are not supposed to be "turned on" in every case study performed according to New-LCA. But in a case study report, it should be made clear which of these elements have been "switched off", what the justification is for doing so, and what the consequence of this is in terms of a restriction of the validity of results.

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

6 ELEMENTS OF THE NEW-LCA-FRAMEWORK

The framework for New-LCA was sketched in Figure 5.12. It consists of three phases: goal and scope definition, modelling, and interpretation. This chapter presents in some detail an exposition of the new-LCA-framework with a subdivision of steps. Wherever possible, the terminology and structure of ISO-LCA will be maintained.

A complication in this is that in ISO-LCA, often a number of aspects are identified, but these are not just steps. For instance, in ISO's goal and scope definition, there are two aspects, namely goal of the study and scope of the study. The latter one is subdivided into issues such function and functional unit and system boundary. Apart from not being a step (for instance, "system boundary" is not an activity, but an issue to consider), most of these aspects reappear in the subsequent inventory analysis and impact assessment, so it is difficult to establish a unique place for such elements.

Therefore, in the following, we have followed the practice as it becomes evident from most published case studies in journals such *The International Journal of Life Cycle Assessment* and the *Journal of Industrial Ecology*. In such LCA studies, the goal and scope definition is restricted to outlining major choices (such as whether to include capital goods), whereas the subsequent phases contain the full discussion (e.g., the detailed flow diagrams).

Below, we will highlight the basic issues of ISO-LCA (so not necessarily in the form of steps), and rephrase and restructure them in several ways:

- to translate them into steps (activities) in a procedural framework;
- to allow for various levels of deepening LCA;
- to allow for various levels of broadening LCA.

Note that the additional topic of CALCAS, the better foundation, is not part of the procedural framework. Rather, it is supposed to be reflected in the steps and the models and data used in these steps.

6.1 Goal and scope definition

ISO 14044 lists here:
I.1) Goal of the study
I.2) Scope of the study
I.2.a) function and functional unit
I.2.b) system boundary
I.2.c) LCIA methodology and type of impacts
I.2.d) types and sources of data
I.2.e) data quality requirements
I.2.f) comparisons between systems
I.2.g) critical review considerations

In the framework for New-LCA, we propose to make one major change in this, namely to add an issue on specifying the question. Which question is asked in the LCA appears to provide a natural place to host a number of issues that are now either not in ISO-LCA or under the scope definition:

- is the analysis geared toward comparing a number of defined products, or toward analyzing a specified product?
- which product is (or which products are) subject to analysis?

- which function of this product is (or which functions of these products are) central in this analysis?
- what is the quantitative measure of this function (or of these functions) and of the context in which it functions?

Note that the term function in this last question is understood in a sense that is broader than in traditional ISO-LCA. It is supposed to be understood as the societal context of the question in terms of scenarios. For instance: In a comparison of two products, A and B, we traditionally assume that the functional unit flattens out differences in functional performance. If one litre of paint A lasts for five years and is sufficient to cover 10 m^2, and paint B lasts for 10 years but can only cover 4 m^2, we can correct this difference in performance by choosing a functional unit in terms of, say 100 $m^2 \times$year of painted surface. This translates then into material requirements of 2 litres of paint A and 2.5 litres of paint B. But this implicitly assumes certain *ceteris paribus* conditions. For example, there might be a difference in price between these amounts of these paints, inducing budget reallocation or change in behaviour. As we have discussed in Section 5.3.3, such mechanisms can be part of the "deeper" New-LCA. The modelling of such mechanisms takes place in the modelling phase, but the decision which mechanisms will be included there is a matter of scope definition. And the definition of the scenarios is part of the specification of the question.

Altogether we end up with the following steps and issues for the revised goal and scope definition:

Steps	**Issues to be considered (examples)**
I.1 Defining the question	comparison or analysis
	which product(s)
	which function(s)
	which functional unit and/or scenario
I.2 Defining the goal	intended application[28]
	reasons for carrying out the study
	intended audience
I.3 Defining the scope	which modelling mechanisms
	which impact types
	system boundary
	critical review
	participatory process

6.2 Modelling

ISO 14044 lists here for inventory analysis and impact assessment taken together:
II.1) Collecting data
II.2) Calculating data
II.2.a) validation of data
II.2.b) relating data to unit process and functional unit
II.2.c) refining the system boundary
II.3) Allocation
II.3.a) allocation procedure
II.3.b) allocation procedures for reuse and recycling
III.1) Mandatory elements of LCIA
III.1.a) selection of impact categories, category indicators and characterization models
III.1.b) assignment of LCI results to the selected impact categories (classification)
III.1.c) calculation of category indicator results (characterization)

[28] This description of the intended application includes the question whether the study is a so-called comparative assertion disclosed to the public.

III.2) Optional elements of LCIA
III.2.a) normalization
III.2.b) grouping
III.2.c) weighting
III.3) Additional LCIA data quality analysis
III.3.a) gravity analysis
III.3.b) uncertainty analysis
III.3.c) sensitivity analysis

The revision from ISO-LCA to New-LCA is more substantial for various reasons:

- breadth: New-LCA is directed to indicators of the social and economic dimension of sustainability, where ISO-LCA concentrates on environmental indicators;
- depth: New-LCA includes more mechanisms than ISO-LCA and allows also for explicit feedback loop from impact to technology, thus requiring a more complex modelling part than merely inventory analysis and impact assessment;
- some issues have been moved to other phases (e.g., f) to the interpretation phase and b.3) has been taken out altogether because iteration is present throughout the framework).

In ISO-LCA the flow diagram represents “the unit processes and their inter-relationships” (14044, p.8). It is a flow diagram in the sense that it represents the flows of materials and energy. In ISO-LCA, unit processes can influence one another in more ways than only through physical flows. Monetary flows provide another mechanism, and so do behavioural changes.

In ISO-LCA no inventory formulas need to be specified, because all unit processes are assumed to be linearly scalable. The specification of process data in that case amounts to what is referred to as model calibration in more general models. In more sophisticated models (e.g., in process chemistry or in economic equilibrium models) the assumption of linearity is relaxed.

In this preliminary stage of defining a framework for New-LCA, the modelling phase is proposed to have the following ingredients:

Steps	**Issues to be considered (examples)**
II.1 Modelling the technological system	flow diagram(s)[29]
	connecting mechanisms between unit processes
	calibration (process data)
	other modelling steps (allocation, cut-off, etc.)
	calculation step 1
II.2 Modelling the satellite systems	modelling the environmental system
	modelling the economic system
	modelling the social system
	modelling the feed-back with the technological system
	calculation step 2
II.3 Calculation of indicators	indicators for the environmental system
	indicators for the economic system
	indicators for the social system
	principles for integration
	calculation step 3

[29] As indicated earlier, flow diagram has a meaning that is generalized from the purely physical meaning in ISO-LCA. It is not a diagram of “things that flow”, but a diagram of how the activity level of one unit process influences the activity level of another unit proecss.

6.3 *Interpretation*

ISO-14044 mentions the following for the interpretation phase:
IV.1) Identification of significant issues
IV.2) Evaluation
IV.2.a) completeness check
IV.2.b) sensitivity check
IV.2.c) consistency check
IV.3) Conclusions, limitations and recommendations

Because we have been moving part of the quality and sensitivity checks from the previous phases to the interpretation, these issues will gain in importance. Moreover, we think that the evaluation should be based on different types of information: the results of the previous phases, the results of sensitivity analyses, the results of a critical review, etc., so that

Altogether we end up with the following steps and issues for the revised goal and scope definition:

Steps	**Issues to be considered (examples)**
III.1 Analysis of the results	consistency check and/or completeness check
	comparative analysis and/or contribution analysis
	uncertainty analysis and/or sensitivity analysis
III.2 Discussion of the results	what can we conclude from the analysis
	what are the limitations of the analysis
III.3 Recommendations	what action can we recommend
	what needs further investigation

7 CONCLUSIONS AND RECOMMENDATIONS

The framework for New-LCA (Figure 5.11) regards LCA as the integrative step in combining empirical knowledge (on technology, on environment, on economics, etc.) and normative positions (on priorities, on ideological questions, etc.). The framework itself needs to be elaborated in terms of formalism (steps, rules, formulas, etc.). And the contributing elements need to be specified as well, although not as part of the LCA, but as truly contributing elements. This chapter briefly explores some of the consequences.

7.1 6.1 What is already there?

At present, the body of knowledge of LCA consists of the following:

- a framework (mainly ISO-LCA);
- methods and rules (e.g., on allocation, on system boundaries, on characterisation);
- data (mainly LCI process data and characterisation factors);
- software (incorporating methods and data);
- a body of literature and experience.

In New-LCA, many of these elements will remain valuable, although sometimes at a different place. For instance, as we consider technical data to be a contributing empirical element to the imtegrative LCA framework, it appears strange to speak of “LCA data”. Rather, LCA uses “technical data on technologies”. The same applies to characterisation data: dose-response functions, GWPs, etc. are not “LCA data”, but represent empirical knowledge that feeds into the LCA process.

7.2 6.2 What is still needed?

Many of the elements in Figure 5.11 are at present not or only incompletely addressed in ISO-LCA. For instance, although there is a number of LCA studies that have incorporated rebound mechanisms, no generally applicable rules have been developed to do so, and no general databases with information on this (demand elasticities?) is available. Thus, within the empirical and normative elements distinguished, many have been studied occasionally, but most have not yet been elaborated into a practically applicable form. It is one of the tasks of the last phase of CALCAS to prioritise the research needs in this respect.

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