Polymer Degradation and Stability 95 (2010) 422–428

Contents lists available at ScienceDirect

Polymer Degradation and Stability

journal homepage: www.elsevier.com/locate/polydegstab

Life cycle assessment and sustainability analysis of products, materials and technologies. Toward a scientific framework for sustainability life cycle analysis

Reinout Heijungs*, Gjalt Huppes, Jeroen B. Guinée

Institute of Environmental Sciences (CML), Leiden University, P.O. Box 9518, 2300 RA Leiden, The Netherlands

ARTICLE INFO

Article history:
Available online 26 November 2009

Keywords:
Sustainable development
Sustainability analysis
Sustainability indicators
Life cycle analysis
Life cycle assessment
LCA

ABSTRACT

There are many approaches to study the environmental and sustainability aspects of production and consumption. Some of these reside at the level of concepts, e.g., industrial ecology, design for environment, and cleaner production. Other approaches are based on the use of quantitative models, e.g., life cycle assessment, material flow accounting and strategic environmental assessment. This paper focuses on the development of a framework that is able to incorporate different models for environmental analysis, with the option of a broader scope that also includes economic and social aspects, thus covering the three pillars of sustainability. This framework builds on the ISO-framework for life cycle assessment, but takes a broader view, and allows us to move from micro questions on specific products, via meso questions on life styles up to macro questions in which the entire societal structure is part of the analysis.

1. Introduction

The advent of the industrial society has been associated with a large number of changes. Many of these changes are beneficial, and many are not. What they have in common that none of these changes were foreseen.

Heinrich Hertz' prediction and discovery (1886) of electromagnetic waves in the end enabled the mass penetration of cell phones and wireless internet, but Hertz perhaps only dreamt of a limited number wireless telegraphs. Likewise, when Alexander Parkes demonstrated the first plastic in 1862, he would never have predicted that plastics would be produced by millions of tonnes 150 years later, and neither that a gigantic island of plastic waste would have developed in the Pacific.

The discovery of electromagnetic waves, the invention of plastic, and other developments have lead to tremendous changes. It is usual to make a distinction between positive and negative effects, and between intended and non-intended effects. This suggests that it is clear cut: that it is always easy to distinguish good from bad, and intended from contingent. This is, however, arguably not the case. Decisions are taken on the basis of available information, and almost always with a narrow focus, e.g. on the short-term profitability. This is, however, in contrast with the idea of sustainability.

The term sustainability has directed policy makers, environmentalists and industrial decision-makers to a broadening of focus in various directions:

- the assessment of costs and benefits has been expanded from private to societal;
- the economic assessment has been expanded to include environmental and social aspects as well;
- the realization that every actor is embedded in a chain of activities has led to the development of notions such as supply chains, the life cycle, and extended producer responsibility.

Such developments have yielded a plethora of concepts, approaches, strategies, policies, models, tools, and indicators. To mention but a few, sustainability analysis, technology assessment, life cycle costing, life cycle assessment, green chemistry, and eco-efficiency attempt to provide an answer to questions regarding the sustainability of chemistry, of industry in general, and of the production-consumption system in an even more general sense. But their sheer abundance presents a conceptual challenge as well: where do they differ, where do they coincide, for which questions is which one useful, do they ever contradict one another, are they complementary, etc.

There is a second issue that deserves attention in this context. It is the question of correctness, validity, reliability. To what extent do analyses with the above-mentioned approaches, strategies, tools, etc.

* Corresponding author. Fax: +31 71 5275587.
E-mail address: heijungs@cml.leidenuniv.nl (R. Heijungs).

0141-3910/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.polymdegradstab.2009.11.010

provide results that stand the test of scientific quality? Is the waste hierarchy based on the 3Rs of reduce, reuse and recycle a soft ideology, a hard scientifically established fact, or a guidance that works in some cases, but that fails in other situations? Are biodegradable plastics preferable to the more traditional ones? Is recycling of waste materials advantageous from a sustainability point of view, or does it only evoke a “feel good” quality?

The two questions, which tool for which question, and how good is the answer from a tool for a certain question, are obviously related. Issues of validity and correctness can only be established by considerations of the scientific quality. This paper seeks to explore the scientific basis of life cycle based tools for sustainability. In doing so, we will first discuss the concept of sustainability, then the concept of life cycle analysis, and finally explore how these two elements can be combined in a scientific framework for decision support.

2. The first element: sustainability

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 [1]. 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” (loc.cit.). 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.

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. But what is a sustainability assessment? Hacking & Guthrie [2] 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 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. 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 are 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 Fig. 1.

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.

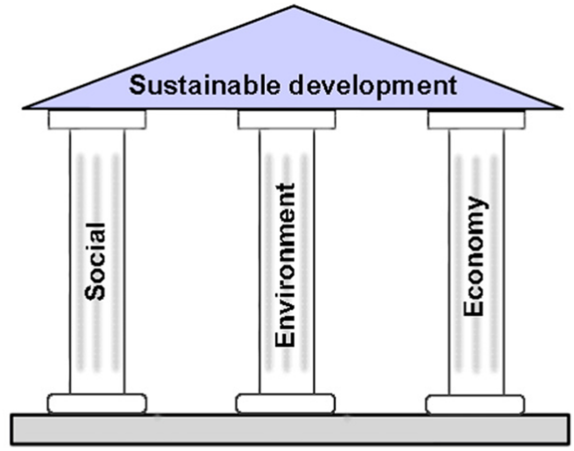

Fig. 1. A popular way of representing SD (taken from http://www.sustainability-ed.org/pages/what3-1.htm). The metaphor expressed is that the three pillars have to be equally well developed in order to sustain the building.

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.

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

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.

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 [3], 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

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 at other places. Following this logic, it is natural to apply a life cycle perspective.

Like sustainability and sustainable development, the terms life cycle and life cycle analysis (or assessment, 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” [4].

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. Businesses have one, and so do policies 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 [4] 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”. 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 [5] 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. Fig. 2 illustrates this idea.

The ISO-14040 standards for LCA have 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 and Pease [6]), they have functioned for a decade in setting the vocabulary, defining the main structure, and providing the context for more elaborate guidelines.

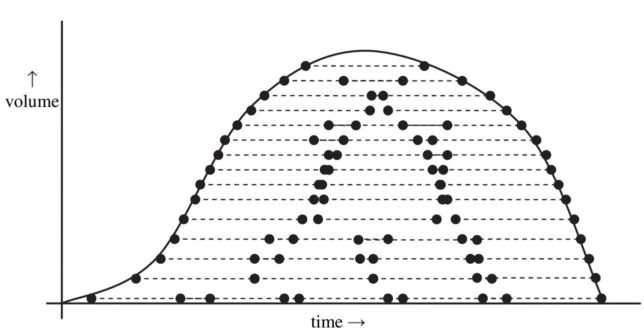

Fig. 2. The collective product life cycle in the business meaning (solid line) as the aggregation of the individual product life cycles in the LCA-meaning (dashed lines with first bullet denoting the cradle and the second the grave of an individual product).

The ISO-LCA framework is shown in the left-hand side of Fig. 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”.

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.

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 [7] stated that LCA “is an objective process”, and that the impact assessment is “a technical, quantitative, and/or qualitative process”. 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 positivism 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. [8]). 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.

4. The two elements combined: life cycle analysis for sustainability

In the previous section, it was seen that LCA is typically restricted to environmental aspects, and that it does so in a simplified way.

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 broader LCA might produce results in the form of an eco-efficiency indicator [9]. Such an indicator includes economic and environmental information, but in a combined way.

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

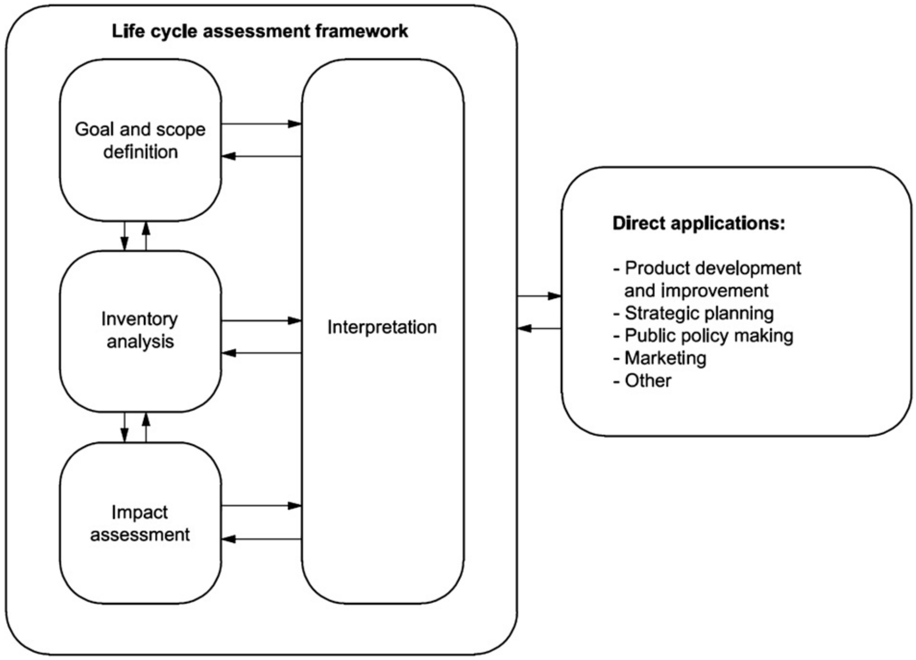

Fig. 3. The LCA-framework according to ISO 14040.

to ignore what is imported from or exported to abroad, and they in general do not account for 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 this paper, the central concept is life cycle assessment for sustainability. This means that the focus is on what might be called life cycle sustainability analysis (LCSA; [10]):

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

In the rest of this paper, 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.

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 are 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 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.

The distinction between data and indicator is an important one. Several authors suggest that one can measure sustainability [11,12], although there are also authors who write on "measuring the immeasurable" [13,14]. 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. 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.

5. General modelling framework

This section 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.

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. 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.

Fig. 4 shows a framework for broader and deeper LCA, separating the empirical knowledge (the "facts"), the normative positions (the "values") and the trans-disciplinary integration (LCA, integrated models, etc.). In the next few subsections, the role and possible content of the different elements in Fig. 4 will be discussed in the form of the models that can address such mechanisms.

5.1. Technical models

Technical models describe the principal causal 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 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, technical models 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) is typically excluded as well.

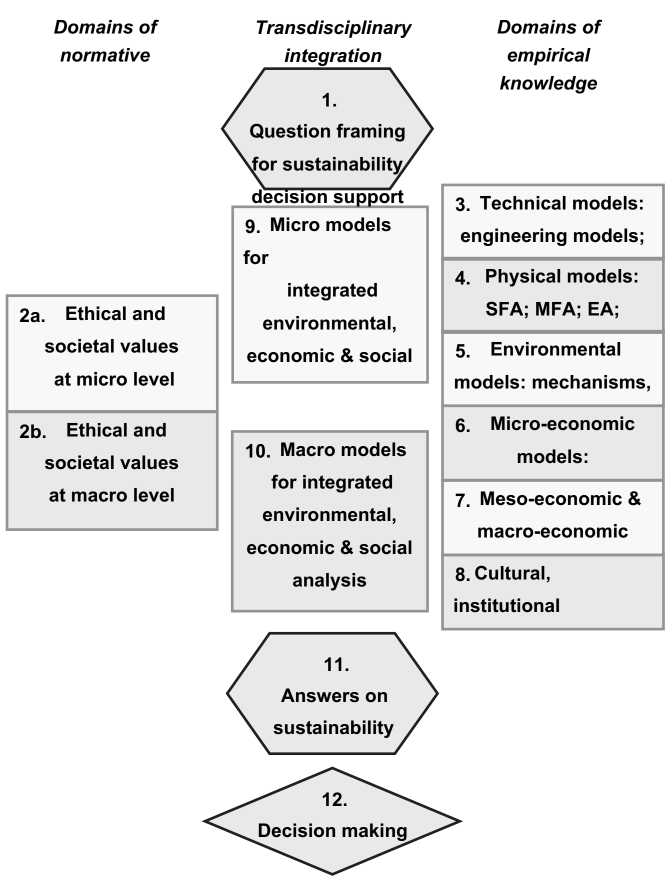

Fig. 4. Framework for LCSA with a separate role for the empirical and the normative elements, and with an explicit integrative role for the tool. Adapted from Huppes & Ishikawa (2009).

5.2. 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 substance flow analysis (SFA) and material flow analysis (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 [15,16].

5.3. 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 modelled by scientists with specific domain knowledge. Their results can be incorporated into LCA models. The same 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.

5.4. 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 modelling. 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 modelling in this respect 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 [17] and Ekvall & Weidema [18] include shifts in market structure as part of the LCA inventory. Likewise, Hofstetter et al. [19] and Thiesen et al. [20] discuss the inclusion of rebound-effects.

5.5. 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.

5.6. 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.

5.7. 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 trans-generational 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).

5.8. Models for integrated environmental, economic & social analysis

This is the place 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.

6. The ISO-framework revisited

Starting with the overview of mechanisms in Fig. 4, we are now ready to present a revision of the ISO-framework for LCA; see Fig. 5. In this framework for so-called New-LCA [21], we have tried to stick to the classic ISO-framework whenever possible. Thus we have established the following correspondences:

- 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

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

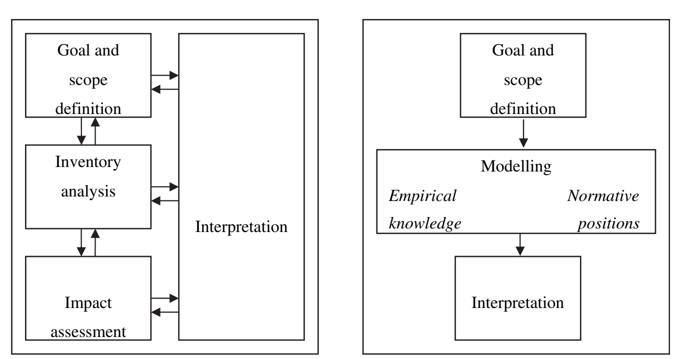

Fig. 5. The ISO-framework (left, taken from ISO, 1997) and the proposed framework for New-LCA (right, taken from [21]). The solid arrows indicate the major information flows only.

"interpretation", we have tried to stay as close as possible to the well-known.

The second issue is more intricate. 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 suffices to reinforce this. The fuel needed to drive 1 km with a certain car depends on technology, drive style, other traffic, traffic policy. So a seemingly technical parameter to specify a unit process depends on the entire complex mentioned (technical models, environmental models, physical models, micro-economic models, etc.). A reductionist separation of this complex into a technosphere and an ecosphere appears rather shallow.

Finally, some words on the broadening of LCA toward a real sustainability analysis. Klöpffer (2008) suggest in a conceptual formula that a life cycle sustainability assessment (LCSA) is an LCA, a life cycle costing (LCC) and a social life cycle analysis (SLCA), done in a consecutive way:

$$\mathrm{LCSA} = \mathrm{LCA} + \mathrm{LCC} + \mathrm{SLCA}$$

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. 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:

- LCA, LCC and SLCA have the same or an equivalent accounting and modelling structure for the inter-industry 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.

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.

Acknowledgment

This paper is based on work done for the CALCAS (Co-ordination Action for innovation in Life Cycle Analysis for Sustainability) project, which has been funded by the EU as part of the 6th Framework Programme (Project no.037075; see http://www.calcasproject.net/).

The work reported has benefited from discussions with project partners (mainly Paolo Masoni, Alessandra Zamagni and Roberto Buonamici from ENEA, Bologna and Tomas Ekvall from IVL, Göteborg) and from discussion with external experts commenting on draft reports and participating in workshops.

References

[1] World Commission on Environment and Development. Our common future. Oxford: Oxford University Press; 1987.
[2] Hacking T, Guthrie P. A framework for clarifying the meaning of triple bottom-line, integrated, and sustainability assessment. Environmental Impact Assessment Review 2008;28:73–89.
[3] Funtowicz SO, Ravetz JR. Uncertainty and quality in science for policy. Dordrecht: Kluwer Academic Publishers; 1990.
[4] ISO. Environmental management – life cycle assessment – principles and framework (ISO 14040). Geneva: ISO; 2006.
[5] Levitt T. Exploit the product life cycle. Harvard Business Review 1965;43(6):81–94.
[6] Hertwich EG, Pease WS. SO 14042 restricts use and development of impact assessment. International Journal of Life Cycle Assessment 1998;3(4):180–1.
[7] Fava JA, Denison R, Jones B, Curran MA, Vigon B, Selke S, et al. A technical framework for life-cycle assessments. Washington: SETAC; 1991.
[8] Hofstetter P. Perspectives in life cycle impact assessment. Boston: Kluwer Academic Publishers; 1998.
[9] Huppes G, Ishikawa M, editors. Quantified eco-efficiency. An introduction with applications. Dordrecht: Springer; 2007.
[10] Klöpffer W. Life cycle sustainability assessment of products. International Journal of Life Cycle Assessment 2008;13(2):89–94.
[11] Figge F, Hahan T. Sustainable value added. Measuring corporate contributions to sustainability beyond eco-efficiency. Ecological Economics 2004;48:173–87.
[12] Spangenberg JH. Environmental space and the prism of sustainability: frameworks for indicators measuring sustainable development. Ecological Indicators 2002;2:295–309.
[13] Bell S, Morse S. Sustainability indicators. Measuring the immeasurable? London: Earthscan Publications Ltd; 1999.
[14] Böhringer C, Jochem PEP. Measuring the immeasurable. A survey of sustainability indices. Ecological Economics 2007;63:1–8.
[15] Cleveland CJ, Ruth M. When, where, and by how much do biophysical limits constrain the economic process? A survey of Nicholas Georgescu-Roegen's contribution to ecological economics. Ecological Economics 1997;22:203–23.
[16] Kåberger T, Månsson B. Entropy and economic processes. Physics perspectives. Ecological Economics 2001;36:165–79.
[17] Weidema B. Avoiding co-product allocation in life-cycle assessment. Journal of Industrial Ecology 2000;4(3):11–33.
[18] Ekvall T, Weidema BP. System boundaries and input data in consequential life cycle inventory analysis. International Journal of Life Cycle Assessment 2004;9(3):161–71.
[19] Hofstetter P, Madjar M, Ozawa T. Happiness and sustainable consumption: psychological and physical rebound effects at work in a tool for sustainable design. International Journal of Life Cycle Assessment 2006;11(Special Issue 1):105–15.
[20] Thiesen J, Steen Christensen T, Kristensen TG, Andersen RD, Brunoe B, Kjaergaard Gregersen T, et al. Rebound effects of price differences. International Journal of Life Cycle Assessment 2008;13(2):104–14.
[21] Heijungs R, Huppes G, Guinée J. A scientific framework for LCA. Deliverable (D15) of work package 2 (WP2) CALCAS project. ENEA, 2009. http://fr1.estis.net/includes/file.asp?site=calcas&file=631CC8B9-1C62-49FC-A2FD-AE82940D0C82.