LCA Methodology

A Decision-Analytic Framework for Impact Assessment
Part I: LCA and Decision Analysis

Edgar G. Hertwich[1] and James K. Hammitt[2]

[1] Energy & Resources Group, University of California, Berkeley, USA, and LCA-Laboratory, Norwegian University of Science and Technology, 7491 Trondheim, Norway; e-mail: hertwich@design.ntnu.no
[2] Harvard Center for Risk Analysis, Harvard School of Public Health, Boston, MA, USA

DOI: http://dx.doi.org/10.1065/lca2000.08.031

Abstract. Life-cycle assessments (LCAs) are conducted to satisfy the aspiration of decision makers to consider the environment in their decision making. This paper reviews decision analysis and discusses how it can be used to structure the assessment and to integrate characterization and valuation. The decision analytic concepts of objectives (goals) and attributes (indicators of the degree to which an objective is achieved) are used to describe steps of the assessment of the entire impact chain. Decision analysis distinguishes among different types of objectives and attributes; it describes how these relate to each other. Impact indicators such as the Human Toxicity Potential are constructed attributes. A means-ends objectives network can show how the different constructed attributes relate to the objective of protecting the environment. As LCA takes disparate environmental impacts into account, it needs to assess their relative importance. Trade-off methods in decision analysis are grouped into utility theory and multicriteria decision aids; they have different advantages and disadvantages, but are all more sophisticated than simple weighting. The performance of the different trade-off methods has not yet been tested in an LCA context. In the second part of the paper, we present criteria for the development of characterization methods.

Keywords: Acidification; decision analysis; evaluation criteria; global warming; human toxicity potential; impact assessment; LCA; life-cycle assessment (LCA); weighting

Introduction

Life-cycle assessment (LCA) is both a quantitative analysis method that builds on factual information and models of natural processes and a judgment process that evaluates the importance of different life-cycle stages and emissions to our concerns about the environment. This dual nature of LCA has triggered a significant debate and has become the subject of a range of papers, commentaries, and PhD theses (Finnveden, 1997; Heijungs, 1998; Hofstetter, 1998; Tukker, 1998; Bras-Klapwijk, 1999; Ekvall, 1999; Lundie and Huppes, 1999; Scheringer, 1999; Frischknecht, 2000). There is the concern on part of the LCA community that the presence of value judgments undermines LCA's standing as an quantitative analytical tool and hence its credibility (Owens et al., 1997; Marsmann et al., 1999). In this paper, we look at decision analysis as a field that, by its very nature, needs to integrate values and factual information. In the first part, we review decision analysis and investigate how LCA can be understood and described as a decision-analytic project. We describe LCA impact assessment in the language of decision analysis. In the second part, we use this framing in the terms of decision analysis to develop a justification for the structure of impact assessment. We show how arguments can be developed about the pieces of information that impact assessment methods should include and how they should be included. We conclude that LCA can be developed as a credible quantitative tool, but that its results will always be dependent on the value choices made during both method development and the assessment process itself.

The values debate that was triggered by the working group on LCA impact assessment of the Society of Environmental Toxicology and Chemistry (SETAC) North America (Owens et al., 1997) and the International Standard Organization's ISO 14042 standard on LCA impact assessment prompted us to investigate the reasoning in LCA. What is LCA? How can it be justified? What can arguments about method choice be based on? How can we distinguish good methods from bad methods, valid from invalid statements? This project lead us to first develop a theoretical, philosophical foundation of LCA (Hertwich et al., 2000). Our central conclusion was that LCA can be justified by its use in decision making. This also guides method development: If LCA is to help decision makers reduce environmental impacts, its methods should be evaluated according to how well they fulfill this purpose. In this paper we continue our exploration of reasoning in LCA by providing an example for how one can construct firm arguments about methodological choices in LCA.

Impact assessment needs to evaluate the relative importance of different environmental stressors (emisssions, resource and land use) related to a life-cycle. This requires the definition of a common metric either for all impacts (e.g., eco-points, $) or for groups of impacts (e.g., CO_2-equivalents, DALYs). The relationship between stressors and their effects is conceptually described by the environmental impact chain in Fig. 1. An important choice concerns the question of whether to grouped similar stressors in categories and evaluate the categories based on fairly solid methods or to attempt an assessment of all impact chains to the final 'value lost'. This 'midpoint vs. endpoint' question will be addressed in the second part of the paper.

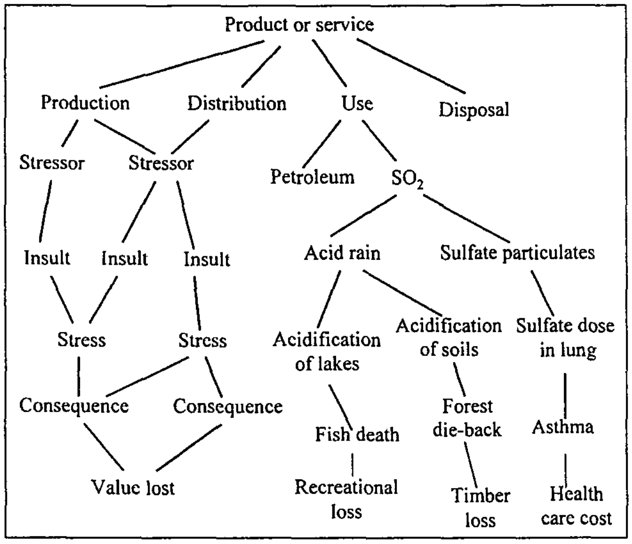

Fig. 1: The impact web describing the connection between stressor and value lost, based on the cause-consequence chain proposed by Holdren (1980). The left shows the terms that are used to describe an impact web. The right presents the example of acid precipitation and a number of its impacts. Each level in the web can be described as being caused by the previous level, and the relationship is described by natural or social processes.

1 Arguments in LCA

Life cycle impact assessment poses a two-fold challenge: on the one hand, the causal chain that links emissions and resource uses to environmental impacts needs to be understood, on the other hand, the importance of the impacts needs to be judged and their relevance to our concerns evaluated. Statements about the relative or absolute importance of environmental stressors contain three different types of claims (Table 1): factual truth claims, which are based on natural science; normative claims, which refer to preference values; and relational claims, which address the proper relation between factual knowledge and values.[1] Objective arguments can be made about each type of claim. The distinction among different types of truth claims is important because the methods used to evaluate the credibility of each type of claim differ. Factual truth claims can be assessed using the scientific method. Normative claims can be based on ethical arguments. The values of individuals or groups can be assessed using various social science methods. Relational claims must follow the rules of logic. In our assessment, much of the controversy and confusion that surrounds the debate about values in LCA derives from a failure to distinguish among different types of truth claims and to recognize differences in the statements that can be made about their validity (Hertwich et al., 2000).

Parallel to the three types of truth claims, we have suggested three validity requirements for LCA methods. As it is apparent in Table 1, the validity requirements refer to the validity of each type of truth claim in LCA. With our distinction of the types of truth claims, we are able to more clearly define the requirements for 'scientific' and 'technical' validity that are part of the international standard for life-cycle impact assessment, ISO 14042.

From the presence of normative elements in LCA, it follows that there exists no unique best impact assessment method. There are different, legitimate sets of preference values and alternative, logically consistent ways of making judgments about facts. In addition, our concerns about the environment demand that we include issues about which no scientific consensus yet exists, e.g. about the causes of observed forest damage. In cases of scientific uncertainty, alternative,

[1] The term 'truth claim' comes from the epistemology of science, a branch of philosophy that investigates how we can know things. A truth claim is an argument that something is correct. The preeminent philosopher of science, Karl Popper (1959), asserted that scientific truth claims, embodied in 'the laws of nature', can never be verified by experimental evidence. We can, however, distinguish between claims that have been shown to be false and those that have not (yet) shown to be false.

Table 1: The types of truth claims in LCA and their associated validity requirements.

	Factual truth claim	**Normative claim**	**Relational claim**
Description	relates to the correctness of the data and scientific models used in LCA	relates to the representativeness, consistency and appropriateness of preference values in LCA	relates to the appropriate use of scientific data and models as well as elicited values to represent our concern about something (relevance, consistency of aggregation)
Example	The persistence of CO_2 in the atmosphere is higher than that of CH_4.	We are more concerned about the near-term effects of climate change than about the long-term effects	Our concerns about climate change are appropriately reflected by the increased infrared absorption resulting from the emissions of a unit of a greenhouse gas integrated over the next 100 years
Requirement	Scientific validity An LCA method is scientifically valid if the factual claims contained in it are scientifically valid[1]	Normative validity An LCA method is normatively valid if the preference values contained in it represent the preferences of actual persons and can be shown to be acceptable in a discussion[2]	Technical validity An LCA method is technically valid if it combines scientific data and models and preference values in a way that is appropriate, logically correct, consistent, and in agreement with the intentions of LCA.

[1] if the claims have not yet been falsified, have a reasonable amount of support, and are consistent with other established scientific knowledge.
[2] ... if the resulting trade-offs are considered to represent reasonable preferences.

legitimate scientific hypotheses may become the factual basis for the assessment. Contextual and constitutive values [described by SHRADER-FRECHETTE (1991) and HERTWICH et al. (2000)] will influence the method choice.

We have also outlined fundamental conditions which affect environmental decision making (HERTWICH, 1999; HERTWICH et al., 2000). Environmental processes are complex and any quantitative description is fraught with uncertainty. Our cognitive ability to process large amounts of data is limited and subject to systematic flaws. Environmental problems are public problems because the detrimental effects are experienced not only by the individuals responsible for them; decisions about environmental protection therefore need to be elaborated in public. Our ability to achieve a consensus on the importance of different issues is inherently limited. For these reasons, an ideal assessment is not feasible and shortcomings have to be accepted as an inevitable feature of any improvement.

In the second part of this paper, we formulate guidelines for method development that are consistent with the validity requirements in Table 1, with LCA's aim, and that consider the implications of the fundamental conditions of environmental decision making.

2 Decision Analysis

'Decision analysis' and 'decision theory' are broad terms that are used interchangeably to group a diverse set of studies of decision making processes, or to label any one of these fields of study. Kleindorfer et al. (1993, 177) group decision analysis into three different subdisciplines: normative, descriptive, and prescriptive decision analysis.

Normative decision analysis studies the logic and mathematics of choice. The prime example is expected utility theory, developed by von Neumann and Morgenstern (1944), which describes rational choice among uncertain prospects. The most actively studied field of normative decision analysis today is game theory, which describes strategic behavior of individuals in situations where the success of an individual depends on the actions other players.[2] More interesting for LCA is social choice theory. Normative theory usually starts from a set of axioms which describe the properties of rational decisions. It studies whether these axioms can be fulfilled, as in Arrow's famous study of social choice, and if these axioms can be satisfied, how they are satisfied. Arrow (1951) has shown that it is impossible to construct group rankings that satisfy a set of plausible minimum requirements for acceptability.

Descriptive decision analysis uses the tools of behavioral psychology to investigate actual human choice and its justification (KAHNEMAN et al., 1982). It reveals interesting patterns of human judgment. Humans exhibit what normative theory would see as systematic flaws in their decision making. They do not act as rational decision makers; rationality is 'bounded' (SIMON, 1957). In contrast to what is suggested by expected utility theory, a long series of experiments has shown that most individuals do not evaluate gains and losses consistently. Their preference for future levels of wealth depends on their current level of wealth, their 'endowment' (KAHNEMAN et al., 1991). While expected utility theory expresses preferences for absolute levels of wealth, individuals evaluate prospects according to changes in the current status. They are usually risk averse for gains and risk taking when it comes to losses instead of consistently displaying risk aversion or risk taking. In addition, Kahneman and Tversky (1979) have found a number of framing effects that indicate that individual behavior does not only depend on the expected outcome of a decision but also on how the decision is presented. These effects have been confirmed in numerous studies and in observations of actual behavior. Medical decision making depends on whether decisions are framed in terms of probability of survival or probability of death. Auto insurance coverage was found to depend on whether drivers were offered a wide coverage with the option to reduce the coverage or a limited coverage with the option to extend their coverage (KLEINDORFER et al., 1993). 'Prospect theory' is the most prominent of several attempts to formulate a descriptive theory which can predict human behavior, but these attempts have not been universally successful (KAHNEMAN and TVERSKY, 1979; SCHOEMAKER, 1991).

Prescriptive decision analysis develops suggestions based on a structured assessment of facts and values. Prescriptive decision analysis has been applied to study big policy questions such as the siting and construction of nuclear waste deposits and airports, as well as the design of computerized decision support tools and expert systems (KEENEY and RAIFFA, 1976; KLEINDORFER et al., 1993; GUITOUNI and MARTEL, 1998). A wide range of methods to trade off different values exists and many of these methods have been implemented in computer-based tools. They differ mainly in the degree to which mathematical consistency of values is emphasized compared to the goal of reflecting and supporting the cognitive processes of human decision making.

The descriptive and normative traditions of decision analysis are interesting because they offer insights and factual knowledge that is relevant also for LCA. Our main interest here, however, is prescriptive decision analysis. We see LCA as a decision support system similar to others designed within decision analysis and hope that LCA can benefit from the lessons learned in the design and use of this broader class of tools.

We will investigate how decision analysis can help us in the valuation phase of LCA and how decision analysis can help us to structure the impact assessment process. In the next section, we will briefly summarize approaches to the tradeoff of preferences in decision analysis. This gives us the opportunity to introduce different approaches to prescriptive decision analysis. In the subsequent section, we structure life cycle impact assessment using the ideas of multiattribute utility theory as described by Raiffa (1968) and Keeney (1992). LCA category indicators or equivalency potentials are *attributes* in decision analysis, and the minimization of the product-related environmental burden is LCA's *objec-*

[2] Note, however, that game theorists also employ empirical studies to study actual behavior of individuals in game theory-like situations.

tive. We show that of the different types of attributes used in decision analysis, *constructed attributes* are most useful in LCA. A *means-ends objective network* can be used to relate LCA indicators to what LCA calls 'safeguard subjects.' An *objective hierarchy* can be used to describe how fundamental the overall objective of protecting the environment can be decomposed into the objectives of protecting the various safeguard subjects.

3 The Aggregation Problem

In LCA impact assessment, environmental stressors are evaluated and evaluations are aggregated. The aim is to obtain statements about the total impact of different products (product A is better than product B) and about the contribution of different components to the overall 'impact' (CO_2 emissions in the use phase are the most important impact of product A; it accounts for x% of the total). Most impact assessment methods consist of simple, linear 'weights' (ecopoints, factors, potentials) which measure the environmental impact per unit of stressor like the price measures the (market) value of a product. The problems with this approach are that it requires that the importance of an attribute be a linear function of the attribute level, and that attitudes towards risk (uncertainty) cannot be taken into account.

There are many approaches to the measurement and tradeoff of different attributes, which we group into two classes. The first group derives from utility theory (VON NEUMANN and MORGENSTERN, 1944) and measures a cardinal utility function for different attribute levels/combinations/probabilities. The most prominent approach is Multi-Attribute Utility Theory MAUT (KEENEY and RAIFFA, 1976). It has been applied to LCA by Miettinen and Hämäläinen (1997). Utility theory is based on mathematical consistency requirements for measurements of the utility of different alternatives and attribute combinations. Its use as a prescriptive approach implies that these consistency requirements should hold for actual decision making. It therefore corrects the 'inconsistencies' observed (by descriptive decision analysis) in individual preferences. MAUT offers a well-developed mathematical structure for describing preference tradeoffs for different attributes taking into account risk attitudes and attribute levels. It is more sophisticated and 'realistic' than the assignment of simple weights in LCA.[3]

The second group is often summarized under the heading of Multi-Criteria Decision Aid MCDA (BANA E COSTA, 1990; PARUCCINI, 1994; GUITOUNI and MARTEL, 1998). The application of MCDA in LCA has been elaborated by Basson (1999). The development of MCDA methods is motivated by the desire that decision support systems should be more intuitive and simpler. MCDA methods recognize that preferences are formed in the process of decision making. The response to problems depends on how problems are presented. MCDAs are situation specific and their application in LCA implies that the relative importance of environmental stressors depends on the specific study. MCDA methods do not use cardinal measures of final impact, and the importance of different contributions (inventory items) can hence not be evaluated easily. MCDA methods may be best suited to supplement the verbal-argumentative valuation approach as described by Giegrich and Schmitz (1997).

The aggregation problem in impact assessment is that there is no entirely satisfying method to evaluate different environmental stressors and aggregate these evaluations to a single score. Traditional weighting methods, including those based on the monetization of environmental externalities, typically assume a fixed trade-off ratio between effects and cannot easily account for attitudes towards risks. Furthermore, the empirical problems with actually assigning weights or prices are well-documented (KAHNEMAN and KNETSCH, 1992). MAUT takes into account risk attitudes and allows for a trade-off that depends on the attribute levels, but it requires more information from decision makers. In its application, MAUT is significantly more difficult than simple weighting methods. MCDA methods may more closely reflect the nature of human preferences, but lack a number of properties desirable for LCA, such as the ability to express the contribution of different stressors or life-cycle steps to the total impact. In addition, the selection of the MCDA method appropriate for a specific problem poses a challenge in itself (GUITOUNI and MARTEL, 1998). We suggest that all three approaches should be developed. Only experience will show which approach is best suited for which LCA application.

4 Objectives and Attributes in LCA

Multiattribute decision analysis uses the concepts of objectives and attributes. Objectives are goals, things we would like to attain or protect. Attributes are measures or indicators that reflect the attainment of the objective. The objective may be to protect human health or to increase productivity. Corresponding attributes could be disease rates or time required to produce one item, respectively. Traditional LCA equivalency potentials or category indicators are attributes.

To structure LCA, we overlay a decision-analytic framework on the impact web. This can be done by identifying objectives and corresponding attributes. Keeney (1992, Chapter 3) distinguishes between fundamental objectives (also called ends objectives) and means objectives. Objectives can be structured through a fundamental objectives hierarchy and through a means-ends objectives network. Keeney also distinguishes among three types of attributes: natural attributes, constructed attributes, and proxy attributes. We will discuss these concepts within the context of LCA.

4.1 Specification of Objectives

Two options are available for specifying a fundamental overall objective. A *fundamental objectives hierarchy* is used to decompose the overall objective. In our case, the objective of protecting the environment can be decomposed into the objectives to prevent human health impacts, to preserve biodiversity, and to prevent significant economic impacts.

[3] Under certain conditions, especially if the contribution to all environmental impacts from a product system is small compared to the total levels of these impacts, the utility functions in MAUT could be reduced to simple weights as they are now used in LCA.

These fundamental objectives can be further detailed. For example, human health impacts can be divided in impacts in current and future generations, in fatal and nonfatal impacts, and according to the health endpoint (cancer, respiratory diseases, heart attacks, etc.). **Fig. 2a** illustrates a fundamental objectives hierarchy. Note that in many cases there is not one single overall objective, but multiple, often competing objectives.

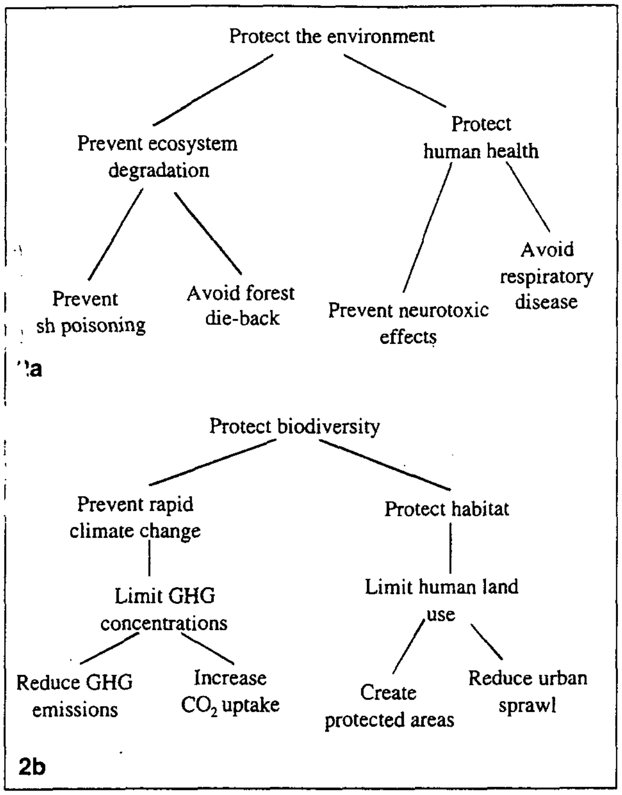

Fig. 2: Objectives can be structured through **(a)** fundamental objectives hierarchy or **(b)** a means-ends objectives network. The hierarchy serves to specify the fundamental objective and decomposes objectives at the level of value lost in the impact web. The means-ends objective network describes actions that are required to achieve the ends of the fundamental objective and goes across depth in the impact chain.

A *means-ends objectives network* is based on causal relationships. "*The lower level objective is a means (that is, a causal factor) to the higher level objective*". The fundamental objective of protecting biodiversity, for example, can be achieved through the protection of habitat, the avoidance of pollution, preventing the alteration of the competitive balance among different species, avoiding the introduction of non-native species, etc. **Fig. 2b** indicates how a means-end objectives network can be use to describe part of the causal chain of the impact web. The means-ends network can be seen as series of actions that are taken to achieve a fundamental objective. To protect biodiversity we would like to avoid rapid climate change. To avoid rapid climate change we need to limit the greenhouse gas concentrations in the atmosphere, which can either be done through the reduction of greenhouse gas emissions or through an increase of CO_2 sequestration by oceans or forests. The means-ends network allows us to describe different elements of the impact chain as objectives; hence we do not need to use the minimization of 'value lost' as an objective, but we can also use the minimization of an appropriately weighted combination of consequences, stresses, or insults.

Fundamental objectives hierarchies and means-ends objectives networks are used for different purposes, as Keeney (1992, 81) notes: "*It is important to recognize that the types of judgments necessary to structure fundamental objectives hierarchies and means-ends objectives networks are distinctly different. Value judgments are required to construct fundamental objectives hierarchies, and judgments about facts are required to construct means-ends networks. Quite simply, deciding what is important requires value judgments. Deciding how to achieve a higher level objective requires factual knowledge.*"

Objectives are reflective of values and there are obviously different ways of structuring the fundamental overall objective of protecting the environment depending on the values of the person who structures these objectives, the purpose of the exercise, and the information available.

The advantage of specifying fundamental objectives through an objectives hierarchy is that it allows us to express fairly general concerns and then describe these in more detail, i.e., it helps us in deciding what is important. It is the lowest level, the most disaggregated fundamental objectives that are used as the operational set of objectives in an assessment.

4.2 Attributes

Attributes are quantitative indicators that are based on useful and relevant information and reflect on the objectives of the decision maker. Keeney (1992, 101f) distinguishes among natural attributes, constructed attributes, and proxy attributes. Since both natural and constructed attributes can be either proximate or direct measures of their objective, we suggest the matrix in Fig. 3 to describe the properties of attributes.

	natural	constructed
direct	number of species lost due to change in vegetation zones	Economic Damage Indicator
proxy	Temperature increase (°C) Increase in CO_2 concentration	Global Warming Potential

Fig. 3: A matrix of attribute properties. Attributes can be grouped according to the dichotomies natural/constructed and direct/proxy. The examples in the matrix represent attributes potentially useful in the discussion of global climate change.

Natural versus constructed attributes: Natural attributes are measurable quantities that directly reflect an objective. For example, the objective of minimizing health effects can be measured by the number of premature deaths caused by pollution. Constructed attributes are based on combinations of information that pertain to the objective. They are not physical quantities that can be measured. Often constructed attributes are based on subjective evaluations of certain features, such as judges' scores in figure skating. Keeney (1992, 103-4) discusses a simpler example: a dichotomous yes-no attribute that reflects the objective to minimize the degradation of hearing with the question whether or not the use of a hearing aid is required after an invasive medical procedure. Keeney notes that these attributes have also been called subjective scale or subjective index. These names, however, are inappropriate because the use of any attribute, even a natural attribute, requires subjective judgment.

Direct versus proxy attributes: Direct attributes immediately reflect the attainment of a fundamental objective. The number of native species in an area is a direct attribute for the objective to preserve biodiversity. Proxy attributes for a fundamental or ends objective indirectly reflect this objective by measuring the achievement of a means objective. Keeney (1992, 103) provides the following example: a fundamental objective is to minimize the damage to historical buildings caused by sulfuric acid. While there is no direct measure for 'stone disfiguration,' the sulfur dioxide concentration in the air is a proxy attribute.

All types of attributes can be useful for LCA. The cancer incidence in a population would be a natural direct attribute. It is a quantity that can be measured, at least in principle. The land area disturbed by industrial activity is a natural proxy attribute for the objective to minimize ecological impacts. The most frequently used attributes in LCA are constructed attributes, such as the Global Warming Potential (WUEBBLES, 1995) and the Human Toxicity Potential (HERTWICH et al., 1998).

"*The careful development of a constructed attribute, with the clarification of the value judgments that are essential to that attribute, may promote thinking and describe the consequences in a decision situation much better than the 'subjective' choice to use a readily available natural attribute.*" (KEENEY, 1992, 104)

There are different types of constructed attributes. Keeney distinguishes among dichotomous yes-no attributes, ordinal attributes, and cardinal attributes. Ordinal attributes are frequently used for a quick assessment of preferences ("One a scale of 1 to 5, ...") and reflect a direct valuation of relevant features of the alternatives. They have several disadvantages. Ordinal attributes do not allow a quantification of uncertainty, because it makes no sense to take their expected value. Nor can they be used to evaluate tradeoffs among attributes, because rates of substitution between attributes are unit-dependent. Ordinal attributes are not useful for LCA inventory data that are normalized in terms of functional unit (e.g. kg of emissions per kWh electricity generated), because they cannot be combined with mass loadings.[4] Ordinal attributes may be necessary to address impact categories for which the impact is difficult to quantify otherwise, such as land use or the degradation of resources. In general, cardinal attributes are more desirable because they can be expressed as attribute per unit of stressor, such as the climate forcing per kilogram of a greenhouse gas.

[4] It is wrong to combine ordinal scales with mass flows, even if this is often practiced.

Many constructed attributes used in LCA also have the character of a proxy attribute, i.e., they reflect a means objective. The Global Warming Potential, for example, reflects th objective to limit the amount of infrared radiation absorb by the atmosphere. The Human Toxicity Potential reflects t objective to minimize the exposure of humans to toxic chemicals. HTP is one step removed from an actual risk assessment but the connection between this means objective and the objective to minimize health effects is very close.

KEENEY provides an extensive discussion of desirable properties of attributes. These properties can be divided into properties that concern the structuring and selection of attribut and properties that concern the tradeoff among the objective reflected by these attributes. The first set of properties are:

1. An attribute should be measurable: "*An attribute th measurable defines the associated objective in more tail. To do this, the attribute must embody implicit va judgments that are appropriate and avoid those that inappropriate.*" (KEENEY, 1992, 113)
2. An attribute should be operational: "*An attribute is c erational if it is reasonable for two purposes: to descri the possible consequences with respect to the associat objective and to provide a sound basis for value judgmen about the desirability of the various degrees to which th objective might be achieved.*" (KEENEY, 1992, 114)
3. An attribute should be understandable: There should b no ambiguity in describing or interpreting consequence in terms of attributes. '*There should be no loss of information when one person assigns an attribute level to describe a consequence and another person interprets that attribute level.*" (KEENEY, 1992,116)

The mathematical form of a utility function can be greatly simplified if certain independence conditions are satisfied. The most important property is that attributes should be *preferentially independent* of each other. A pair of attributes is preferentially independent of other attributes if the preference order for consequences involving changes in the levels of those two attributes does not depend on the level of other attributes (KEENEY, 1992, 133). The preferential independence condition is not fulfilled by some of the LCA indicators, because natural processes sometimes interact. A cooling of the stratosphere through increased greenhouse gas concentrations increases stratospheric ozone depletion in polar regions. The attributes 'CFC concentrations' and 'greenhouse gase concentrations' are not preferentially independent.

4.3 Structuring LCA Using Objectives and Attributes

Fig. 4 indicates how attributes and means-ends objectives can be used to describe the impact web. Attributes quantitatively describe the relationship down the impact web, from stressor to insult etc. Each impact category is represented by a means objective, in Fig. 4 the minimization of acidic emissions. This means objective is described by a constructed attribute; e.g. the number of acidic ions introduced to the environment through the emissions listed in a life-cycle inventory. The means-ends objectives network is then used to relate the means objective to the fundamental or ends objectives. Note that a single attribute represents a number of impact chains that relate to the same means objective. A single means objective can relate to several ends objectives reflecting the impact of acid rain on welfare and ecosystems.

If objectives and attributes are used to structure LCA, a number of questions arise. How do we identify the stressors that should be grouped into a single impact category? What should the means objective and the corresponding attribute be? This is also a question about the appropriate depth of analysis: where in the impact chain should the means objective be located? What information should be included in the attribute? And how is the means-ends objectives network organized? In the second part of this paper, we try to develop criteria, rules, and suggestions for these decisions.

The structure of Life Cycle Impact Assessment suggested by SETAC (FAVA et al., 1993) involves two steps of comparison. In the characterization step, stressors within a single category are compared and aggregated. Categories group stressors that act by similar mechanisms of action or affect similar endpoints. In the valuation step, different categories are compared among each other. While the two-step comparison procedure is well established as a conceptual ideal, more sophisticated procedures are often used in practice. The Eco-Indicator 95 project uses a three step procedure (GOEDKOOP, 1995). It uses established characterization procedures to aggregates stressors within categories. Then it relates these categories to the 'safeguard subjects' of human health, ecological health, and welfare. These three categories are then compared to each other.

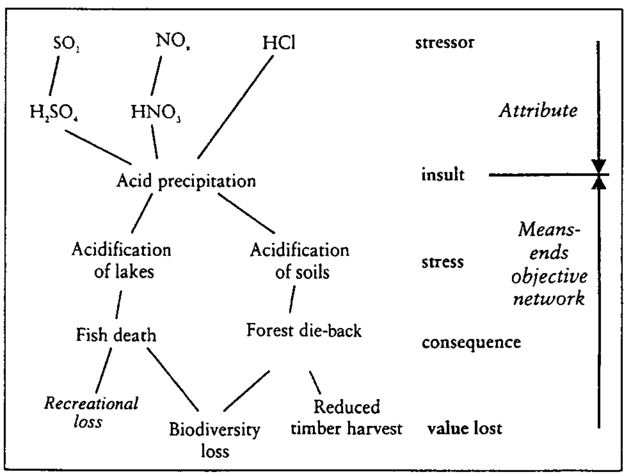

Fig. 4: Structuring of objectives and specification of attributes in life cycle impact assessment: Several impact chains can be grouped together because there is a common mechanism of action going from the insult to the value lost. The commonly used attribute for the acidification category - [H^+] loading or SO_2 equivalents - describes an insult; the remainder of the causal chain is then left to be evaluated by 'valuation.' It can be described by a means-ends objectives network.

In a three-step procedure, the first step would be the assessment of constructed attributes, the second step would relate the means objective represented by the attributes to the ends objectives, and the third step would evaluate the importance of different ends objectives. In practice, even more steps may be desirable to aggregate increasingly less similar impacts. For example, in an intermediate step the impacts evaluated with the human toxicity potential could be compared to the human health impacts resulting from tropospheric ozone using a similar model environment. Comparison and aggregation should occur where similarities among the impact chains exist.

5 Preliminary Conclusions

Life-cycle impact assessment closely matches the structure of prescriptive decision analysis. Category indicators in LCA can be described as attributes, while safeguard subjects correspond to fundamental objectives. Decision analysis hence offers a field in which more and more general experience has been gained with the issues of how to structure the analysis and how to trade off different attributes. In the second part of this paper, we will develop criteria for the structuring of the analysis and discuss two alternative approaches that have become known as 'midpoint modeling' and 'endpoint modeling.'

Previously, we have established that there exists no unique best indicator for environmental harm, because evaluations of environmental detriment can be based on different, legitimate sets of values and on competing, justifiable notions of rationality. The present review of decision analysis indicates that there is no single 'best method' for trading off values. Principled evaluations of the advantages and disadvantages of various approaches, however, are still possible. Given a certain application, it can be shown that one method is better than others. Some may be found to be unacceptable. Among a plurality of legitimate ways of both structuring the assessment and trading off values, each method will have certain deficiencies. The demonstration of deficiencies is hence not sufficient reason to dismiss a method. Instead, an alternative method that better fits the given purpose has to be found.

References

Arrow, K. J. 1951. Social choice and individual values. New York: Wiley.

Bana e Costa, C. A. 1990. Readings in multiple criteria decision aid. Berlin: Springer-Verlag.

Basson, L. and J. G. Petrie. 1999. Decision Making during Early Stages of a Project Life Cycle: Roles for Multiple Criteria Decision Analysis, Life Cycle Assessment and Ecological Risk Assessment, SETAC 20th Annual Meeting, Philadelphia, Society of Environmental Toxicology and Chemistry.

Bras-Klapwijk, R. M. 1999. Adjusting Life Cycle Assessment Methodology for Use in Public Policy Discourse. Delft: Delft University of Technology: 280.

Ekvall, T. 1999. System Expansion and Allocation in Life Cycle Assessment with Implications for Wastepaper Management. Technical Environmental Planning. Göteborg: Chalmers.

Fava, J., F. Consoli, R. Denison, K. Dickson, T. Mohin and B. Vigon, Eds. 1993. A Conceptual Framework for Life-Cycle Impact Assessment. Pensacola, Fl, Society of Environmental Toxicology and Chemistry.

Finnveden, G. 1997. Valuation Methods Within LCA - Where are the Values? Int. J. LCA 2(3): 163-169.

Frischknecht, R. 2000. Allocation in life cycle inventory analysis for joint production. Int. J. LCA 5(2) 85-95.

Giegrich, J. and S. Schmitz. 1997. Valuation as a Step in Impact Assessment: Methods and Case Study. In Environmental Life-Cycle Assessment, edited by M. A. Curran. New York: McGraw-Hill.

Goedkoop, M. 1995. The Eco-indicator 95, 9523. Utrecht, NL: Netherlands Agency for Energy and the Environment, National Reuse of Waste Research Programme (NOH).

Guitouni, A. and J. M. Martel. 1998. Tentative guidelines to help choosing an appropriate MCDA method. Eur. J. Oper. Res. 109(2): 501-21.

Heijungs, R. 1998. Towards eco-efficiency with LCA's prevention principle: an epistemological foundation of LCA using axioms. In Product Innovation and Eco-efficiency, edited by J. E. M. Klostermann and A. Tukker. Dortrecht: Kluwer: 175-186.

Hertwich, E. G. 1999. Toxic Equivalency: Accounting for Human Health in Life-Cycle Impact Assessment. Energy and Resources Group. Berkeley: University of California: 237.

Hertwich, E. G., J. K. Hammitt and W. S. Pease. 2000. A Theoretical Foundation for Life-Cycle Assessment: Recognizing the Role of Values in Environmental Decisionmaking. J. Ind. Ecol. 4(1): 13-28.

Hertwich, E. G., W. S. Pease and T. E. McKone. 1998. Evaluating toxic impact assessment methods: What works best? Environ. Sci. Technol. 32(5): A138-A144.

Hofstetter, P. 1998. Perspectives in Life Cycle Impact Assessment: A Structured Approach to Combine Models of the Technosphere, Ecosphere and Valuesphere. Boston: Kluwer.

Holdren, J. P. 1980. Integrated Assessment for Energy-Related Environmental Standards: A Summary of Issues and Findings. LBL Report 12799. Berkeley: Lawrence Berkeley Laboratory.

Kahneman, D. and J. L. Knetsch. 1992. Valuing Public Goods: The Purchase of Moral Satisfaction. J. Environ. Econ. Manage: 57-70.

Kahneman, D., J. L. Knetsch and R. H. Thaler. 1991. Anomalies: The Endowment Effect, Loss Aversion, and Status Quo Bias. J. Econ. Perspect. 5(1): 193-206.

Kahneman, D., P. Slovic and A. Tversky. 1982. Judgment under uncertainty: heuristics and biases. Cambridge: Cambridge University Press.

Kahneman, D. and A. Tversky. 1979. Prospect Theory: An Analysis of Decision Under Risk. Econometrica 47: 263-291.

Keeney, R. L. 1992. Value-Focused Thinking: A Path to Creative Decisionmaking. Cambridge, MA: Harvard University Press.

Keeney, R. L. and H. Raiffa. 1976. Decisions with multiple objectives: preferences and value tradeoffs. New York: Wiley.

Kleindorfer, P. R., H. C. Kunreuther and P. G. H. Schoemaker. 1993. Decision Sciences: An Integrative Perspective. Cambridge: Cambridge University Press.

Lundie, S. and G. Huppes. 1999. Environmental Assessment of Products--The Ranges of Societal Preferences Method. Int. J. LCA 4(1): 7-15.

Marsmann, M., S. O. Ryding, H. Udo de Haes, J. Fava, W. Owens, K. Brady, K. Saur and R. Schenck. 1999. In reply to Hertwich & Pease Int. J. LCA 3(4), S. 180 – 181 'ISO 14042 Restricts Use and Development of Impact Assessment'. Int. J. LCA 4(2): 65.

Miettinen, P. and R. P. Hämäläinen. 1997. How to benefit from decision analysis in environmental life cycle assessment. Eur. J. Oper. Res. 102(2): 279-294.

Owens, J. W., L. Barnthouse, J. Fava, K. Humphreys, B. Hunt, S. Noesen, J. A. Todd, B. Vigon, K. Weitz, et al. 1997. Life-Cycle Impact Assessment: The State-of-the Art. Pensacola, Fl: Society of Environmental Toxicology and Chemistry.

Paruccini, M. M. 1994. Applying multiple criteria aid for decision to environmental management. Dordrecht: Kluwer.

Popper, K. R. 1959. The logic of scientific discovery. New York: Basic Books.

Raiffa, H. 1968. Decision Analysis. Reading, MA.: Addison-Wesley Publishing Co.

Scheringer, M. 1999. Persistenze und Reichweite von Umweltchemikalien. Weinheim, Germany: Wiley-vch.

Schoemaker, P. J. H. 1991. Choices Involving Uncertain Probabilities: Tests of Generalized Utility Models. J. Econ. Behav. Organ. 16: 295-317.

Shrader-Frechette, K. S. 1991. Risk and rationality: philosophical foundations for populist reforms. Berkeley: University of California Press.

Simon, H. A. 1957. Models of Man. New York: Wiley.

Tukker, A. 1998. Uncertainty in Life Cycle Impact Assessment of Toxic Releases. Int. J. LCA 3(5): 246-258.

von Neumann, J. and O. Morgenstern. 1944. Theory of games and economic behavior. Princeton: Princeton University Press.

Wuebbles, D. J. 1995. Weighing Functions For Ozone Depletion and Greenhouse Gas Effects On Climate. Ann. Rev. Energy Environ. 20: 45-70.

Received: February 15th, 2000
Accepted: June 3rd, 2000
Online-First: August 21st, 2000