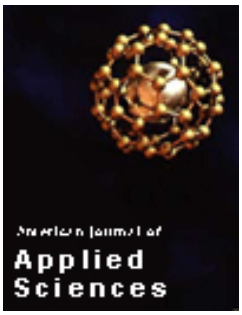
Integrating Life Cycle Assessment and Other Tools for Ex Ante Integrated Sustainability Assessment in the Minerals Industry



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Abstract

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Abstract: Problem statement: The minerals industry is faced with choices beginning in the exploration phase and extending over the life cycle of the mine. Firms examine the technical feasibility of alternative actions and typically rank them based on economic performance. Increasingly firms also consider alternatives' contribution to sustainable development. **Approach:** Sustainable decision making before investment (ex ante decisions) should incorporate a broad suite of quantitative and qualitative information. One approach is to utilize an Integrated Sustainability Assessment (ISA) framework that supplements traditional technical and financial tools with other tools such as Objectives Hierarchies (OH) and Life Cycle Assessments (LCA). The outputs of these tools can be combined with additional qualitative measures and analyzed using Multi-Criteria Decision Analysis (MCDA). **Results:** Our paper extends previous literature by discussing how a combined OH-LCA-MCDA can support ex ante sustainability assessment by incorporating preferences, risk attitudes and monetized, non-monetized social and economic variables in a manner that captures their inherent complexity. **Conclusion:** Sustainable development is not a destination; it is an ongoing journey that must be supported by knowledge, social learning and adaptation. Decisions made in the context of sustainability are likewise part of an ongoing process. No single tool can adequately support an ISA. Multiple tools are necessary, with each used in a manner consistent with its strengths.

Key words: Life cycle assessment, integrated sustainability assessment, objectives hierarchies, multi-criteria decision analysis, Willingness To Pay (WTP), likewise part, combination circuit

INTRODUCTION

Firms frequently face situations where decisions must be made. In the case of mining, the decisions include where to spend exploration dollars, which deposits warrant scoping, prefeasibility or final feasibility studies, whether to develop a project or shelve it for the time being, which piece of equipment to purchase, or which beneficiation process to utilize. In many cases the decisions concern objects or systems that are statically and dynamically complex, e.g., ball mills, which embody static complexity in design, but dynamic complexity when running as part of a combination circuit. Selection of the pieces of equipment and design of the circuit can be accomplished with existing quantitative tools and methods. However, the circuit does not stand alone. Rather it resides within a wider industrial system that in turn interacts with other technologies, as well as human and environmental systems.

When these types of systems have attributes of uncertainty, connectivity and in some cases urgency, they are termed wickedly complex (Conklin, 2005). They cannot be definitively described by narrow, partial equilibrium approaches (Allenby, 2011; Shields *et al*., 2002; Stock and Burton, 2011). Moreover, decisions associated with such systems are seldom clear cut or globally optimal. They are more correctly thought of as better or worse depending, upon the goals driving the decision and the distribution of subsequent risks and consequences. A framework is needed that can deal with open, dynamic and integrated systems and that acknowledges the interconnectness of society, the economy and the environment (O'Connor, 2006). Sustainable development is one such paradigm. It is a process, a series of incremental actions, rather than a destination and as such can be thought of as a frame for

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interactive assessment and decision making intended to achieve an evolving set of goals.

Whenever a decision is made, three overarching questions will frame the process: who has a voice, what information is relevant and what approach or tools will be used to inform and reach the decision. How these questions are answered reflects the values and direction of the organization, its strategic objectives, policies and goals. There are many visions of what a sustainable future should look like and much debate about what should be sustained. Each alternative course of action has the potential to further progress toward one or more sustainability goal. Inevitably, trade-offs and choices have to be made about what to sustain, by which means, when to do so and who gets to decide.

Once a firm embraces sustainability as a core value, the range of groups and individuals who need to be informed and engaged, who deserve to have at least a voice, expands substantially. Their objectives and values need to be considered whenever a decision has the potential to affect their health, well-being, livelihoods or communities MMSD, 2002. Moreover, greater transparency is required (Payet, 2003). Firms that embrace and practice Corporate Social Responsibility (CSR) take transparency, best practice, accountability and risk assessment (among other issues), into account (Kogel *et al*., 2006).

The answer to the second overarching question, what information is relevant to the decision, depends upon not only the complexity of the question to be answered, but also the answer to the first question: whose interests are to be addressed in the decision process. In the past, a mining firm might have made a decision internally and exclusively on engineering grounds (e.g., where to place a tailings disposal facility), on the outcome of a financial analysis (e.g., what size haul trucks to use), or based on relative environmental impact (e.g., use of municipal solid waste versus petcock for clinker burning). However, decisions informed by a comprehensive sustainability perspective, ones that include stakeholders in the process, will require a much greater range of information, so as to be responsive to the objectives and concerns of all interested parties.

Turning to the third question, a variety of tools can be used, singly or in combination, to make comparisons among alternatives. They range from the simple (checklists, decision trees, questionnaires and rules of thumb), to the more formalized (cost-benefit analysis, environmental impact assessment, risk assessment and financial analysis), to complex (life cycle analysis, multi-criteria decision analysis and systems modelling). The supporting literature for each is vast and multi-disciplinary and review of all available decision tools is beyond the scope of this paper (Azapagic and Perdan, 2005a; b; IVM/IES, 2006; Jäger and Bohunovsky, 2008; Petrie *et al*., 2007; Singh *et al*., 2009; Zopounidis and Doumpos, 2002). Some, however, are particularly well suited to problem structuring and ex ante sustainability assessment and we focus on a select group of those methods.

We begin by introducing the concept of an integrated sustainability assessment (ISA). We then describe the conceptual similarities, differences and overlaps among several available problem structuring and analysis tools, noting where they can contribute to an ISA. With emphasis on the minerals industries, we discuss the strengths and weaknesses of each, as well as the benefits of using the tools in conjunction. We conclude that no single tool can adequately support an ISA. Multiple tools are necessary, with each used in a manner consistent with its strengths.

MATERIALS AND METHOSDS

Integrated Sustainability-based Assessments (ISA): An ISA is a process through which the expected effects of a project, investment or policy are examined within the context of sustainability principles (Jäger and Bohunovsky, 2008). It is an integrative and active process (Weaver and Rotmans, 2006). This type of assessment sets a higher test for investment or policy approval than has been the case in the past. The goal is to facilitate the selection of technically and economically feasible alternatives, that can reasonably be expected to earn a profit (when applied in a business context), while also being environmentally and socially sustainable and acceptable to stakeholders. Sustainability assessments should take a multi- or trans-disciplinary approach, combining data and information from a variety of sources and utilizing the skills of different professionals and stakeholders, including traditional or indigenous knowledge where appropriate (Stock and Burton, 2011). In addition, this type of deal with the specifics of context.

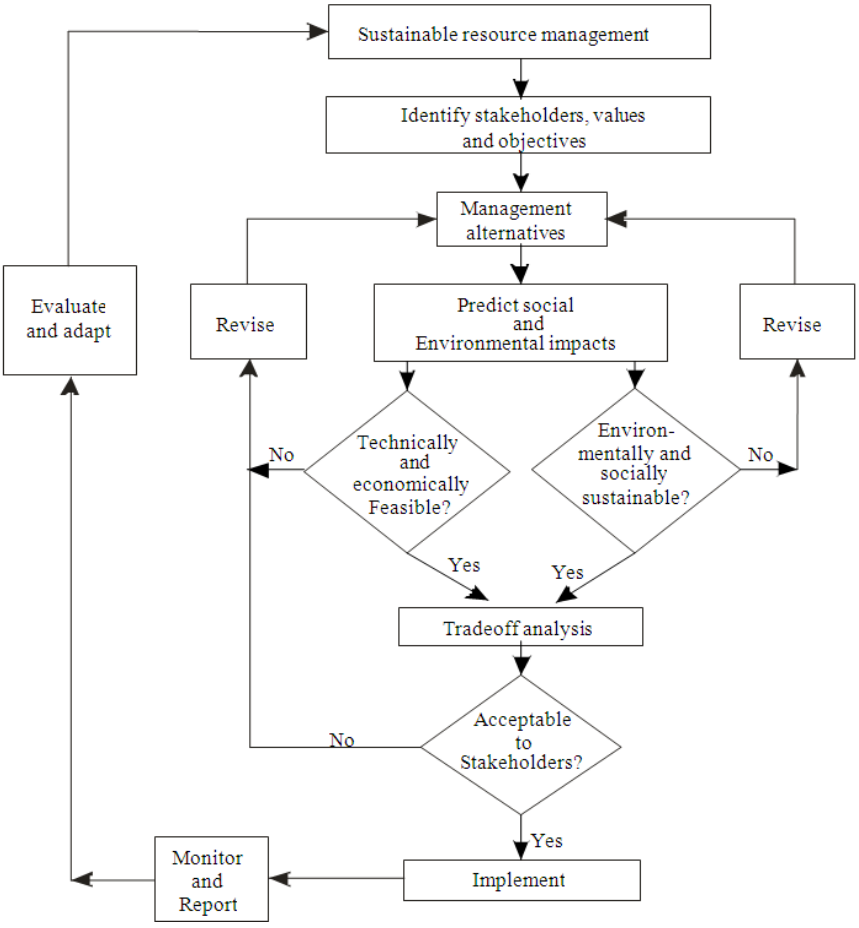

Fig. 1: Iterative, integrated sustainability assessment (Shields and Šolar, 2004)

The various steps of an ISA need to take place within a broader decision framework that integrates knowledge about a problem and makes it available for societal learning and decision making (Bohunovsky and Jäger, 2008; Keen *et al*., 2005; Wallis *et al*., 2010). This framework comprises a set of procedures that connect the various parts of a decision making process and within which a range of different analytical tools can be applied (Finnveden *et al*., 2003).

Shields and Šolar (2004) described such an ISA framework as it would apply in resource management (Fig. 1). Assessment begins with the identification of stakeholders, their value sets and objectives related to the project under consideration and the land, communities and people it has the potential to impact. This step is directly related to and overlaps scope definition for the project or investment; however, the scope of traditional assessment is defined by the firm, perhaps with input from financial institutions and shareholders, whereas the authors' approach is explicitly a multi-stakeholder process. Scope should incorporate economic, environmental, social and technical aspects. It should also take into account spatial and temporal scales and the feasibility of obtaining the information (Rapport, 2003). Scope should be broad enough to include all relevant system components and address the major concerns of stakeholders, while also narrow enough that site specific detail is not lost.

Alternative approaches for dealing with the management situation or investment opportunity under consideration are developed, which address the objectives of the firm, the expectations of financiers and shareholders, legal requirements and the desires and needs of stakeholders to varying degrees. The set of alternatives cannot be exhaustive due to costs, but should cover a range of methods and tactics.

There may be situations where, due to technical considerations, only one development option or engineering process is viable, but even in such cases an

ISA should be conducted to determine if implementation is environmentally and socially acceptable. For example, there may be situations where development of a mineral deposit is precluded because the ISA demonstrates high potential for significant damage to a World Heritage Site if the only available technology is implemented.

Once a set of alternatives has been laid out, the social and environmental impacts of each are predicted, which implies that baseline system information will be collected and analyzed. This baseline can be thought of as a 'no change' alternative for comparison purposes. Technical aspects are considered in more detail and economic analyses conducted, in each case using appropriate techniques. Technically or economically infeasible and socially or environmentally unsustainable, alternatives are revised or rejected. Trade-off analysis is then conducted across the feasible alternatives to identify which objectives can and cannot be met is each case. Results are shared with interested parties. Assuming a mutually acceptable alternative can be identified, or constructed from the initial set of alternatives, it is implemented, monitored and evaluated. Ideally, public engagement would be ongoing and at least some monitoring data shared. Over time, adaptation and revision will almost undoubtedly be needed, which will again require more formalized public participation. (We recognize that some development proposals are so controversial that universally acceptable alternatives do not exist; however, investigation of the implications of such scenarios is beyond the scope of this paper.)

ISAs are thus conceived as iterative processes. The first cycle occurs ex ante, just as have prefeasibility and feasibility analyses (Darner, 2003). The monitoring and evaluating steps comprise ongoing assessment, which also entail reporting on the sustainability of the project GRI, 2009. In theory, ex ante and ongoing assessments could utilize the same methods. Also, in some cases a more simplified approach is used during initial screening processes (Graedel and Allenby, 2010). Ex post assessment is done at the end of an action, e.g., after the completion of a project or activity such as completion of mine reclamation. The goal is to evaluate the accuracy of ex ante predictions and quality and responses to ongoing assessments and to determine if different actions could have led to better outcomes.

The ISA framework combines outputs from various tools in such a way that they can be viewed and interpreted as a whole. Tools for ISA have been categorized based on type: (a) participatory, (b) scenario, (c) multi-criteria analysis, (d) cost-benefit and cost-effectiveness analysis, (e) models and (f) accounting and physical analysis tools and indicator sets, as shown in Fig. 2 (IVM/IES, 2006). Different tools are appropriate, or in some cases best suited, for different phases of an ISA: I - problem analysis, II - finding solutions, III - sensitivity analysis and IV - follow-up.

As noted earlier, the range of possible techniques is vast. We therefore limit our discussion to a the first and third phases and to a subset decision tools that support analysis of projects that have the following characteristics: multiple stakeholders, with unique objectives, preferences and levels of risk tolerance; a decision context with quantitative and qualitative aspects; and one for which there are multiple alternatives, each of which has different benefits and impacts accruing to different stakeholders. We first compare three problem structuring approaches, sustainable development hierarchies, objectives hierarchies (sometimes called value trees) and Life Cycle Assessment (LCA), the graphical form of which resembles and is also termed a value tree (Seppälä *et al*., 2001). We next briefly describe multi-criteria modeling concepts, because these methods were specifically developed to combine qualitative and quantitative data, as well as incorporate measures of preference, uncertainty and risk attitude. Life Cycle Assessments (LCAs) also can utilize values and preferences in later stages and are frequently used to rank alternatives. Through a subsequent process of comparison and discussion, we demonstrate how these tools are similar and the strengths and weaknesses of each in handling the range of data and issues associated with an ISA. Our goal is to show that for the types of complex problems that exhibit the characteristics described above, there are benefits to utilizing these tools sequentially in an ISA, rather than one or another exclusively.

Sustainable Development Hierarchies (SDH): A sustainable Development Hierarchy (SDH) is a framework comprising goals, principles, criteria and indicators (Lammerts van Bueren and Blom, 1997). In the context of this discussion, the overarching goal could be the sustainable management of a mine or industrial project. Principles lay out the implicit and explicit elements of sustainable management; they should have the character of an objective and contain fundamental laws or rules stated in terms of the primary goal. Criteria then translate the principles into system characteristics and desirable system states or dynamics. Criteria capture the elements of what it means to be sustainable in the project context. The elements of each criterion are the indicators of sustainability, which are populated with data measurements. Often verifiers or thresholds are associated with each indicator; they represent the level above or below which an indicator is at an acceptable or unacceptable level.

	Phase 1 Problem analysis	Phase 2 Finding solutions	Phase 3 Analysis	Phase 4 Follow-up
Participatory tools	Problem framing	Support scenario building	Providing the context for and improve robustness of MCA, CBA and CEA	Quality assurance
Scenario tools	Providing the future perspectives to problem framing	Visioning (including uncertainty analysis)	Reference for the application of other tools	–
Multi-criteria analysis tools (MCA)	–	Definition of criteria	Compare different alternatives	–
Cost-benefit analysis (CBA) and cost effectiveness analysis (CEA) tools	–	Definition of criteria	Compare different alternative	–
Model tools	Supporting problem framing	Supporting scenario construction	Full characterization of scenarios to enable comparison	Ex-post assessment
Indicator tools				

Fig. 2: Tool groups and roles in integrated sustainability assessment (IVM/IES, 2006)

Each descending level of the hierarchy describes with increasing specificity what should be accomplished in support of the overarching goal of a sustainable engineering project. This hierarchical approach ensures that the connections between an indicator and the criteria and principles that the indicator refers to, are clear. The likelihood of redundancy is reduced, while the likelihood of complete coverage is increased, consistent with Keeney and Raiffa's (1993) rules on indicators.

A core tenet of sustainable development is the need to balance, or at least acknowledge trade-offs among social, economic and environmental aspects of complex systems and an SDH will have goals, principles, criteria and indicators related to each category. Because stakeholder participation is also core to sustainability, an SDH is typically created collaboratively with multiple interested parties. Through this process differences in opinion and perspective about the meaning of sustainability, the relative importance of various criteria and indicators and the values of participants are shared. The SDH process can clarify legitimate differences of opinion among stakeholders about what to sustain, where and when to sustain it, for whom and how.

The indicators can be evaluated individually, with the goal of determining the degree to which specific criteria are being or could be reached. However, to evaluate the sustainability of the entire system, indicators need to be considered as a group. This can be done qualitatively or quantitatively and in the latter case necessitates normalizing the indicators so their magnitudes are relative and assigning weights that represent relative importance of each. Decision theoretic methods such as swing weighting (Von Winterfeld and Edwards, 1986) or analytical hierarchy process (Saaty, 1990) can be used. These weights will differ across stakeholders and thus, the set of indicators can and probably will be interpreted differently, depending upon perspective and preferences. Once weights are assigned the set of indicators can be combined using a variety of mathematical or decision theoretic approaches. Merely summing normalized indicators does not mean weighting has not taken place; it means that all indicators are weighted equally and so are assumed to be equally important.

Value trees and Objectives Hierarchies (OH): Keeney (1993) has argued that values are really the driving forces for decision-making and as such should be explicitly acknowledged because they will be the ultimate basis for evaluation. Values are made explicit through objectives, i.e., people select as objectives those things, states of being, or system characteristics that they consider valuable. Similarly, the principles and criteria in an SDH reflect what is thought to be important (valuable) enough that it should be sustained. An objective is a statement of what one desires to achieve and is characterized by having a context (in this instance, mining), an object (a project alternative) and a direction of preference (e.g., fewer particulate emissions is better).

Information on objectives is organized into an Objectives Hierarchy (OH) (Keeney and Raiffa, 1993). This tree-like representation of an individual's or group's objectives is frequently referred to as a value tree. It is an ordered relationship, from objectives to measures. Overarching strategic objectives reside at the highest level and explicitly or implicitly guide all decision making. The upper-most objectives "make explicit the values one cares about in [the decision or project] context and define the class of consequences of

concern" (Keeney and Raiffa, 1993). They are thus comparable to sustainability principles. In a business context, strategic objectives are expressions of the firm's core values, such as their commitment to sustainable management. Mid-level objectives represent specific characteristics of the desired end state and so are comparable to criteria. There may be additional layers of objectives, if more detail is necessary, including objectives related to the means by which upper level objectives are to be achieved. Finally, attributes are assigned to the lowest level objectives of the tree structure. An attribute is a relevant property of an entity or system, or a relevant relationship within or between systems (Moon *et al*., 1998). Again, attributes are linked to measurable data.

An OH can contain objectives related to society, the economy and/or the environment; however, the objectives are not typically stated in terms of something to be sustained, but rather in terms of a system feature or condition of interest. Unlike an SDH, there is no a priori assumption that all aspects of sustainability will be included. An OH can be and often is very narrowly defined. Neither is there a tradition or rule recommending that stakeholders be included in the development of the OH, though it is certainly possible to do so. In some cases in corporate decision settings, the OH is developed by company employees, which is completely appropriate when the decision has consequences for and impacts only within the firm.

As in the case of sustainability indicators in the SDH, the meaning derived from a set of attributes is open to interpretation and is a function of both the weighting scheme and method chosen to combine the normalized weighted attributes. Often the method is some form of multi-criteria decision model, as will be discussed later.

Life Cycle Assessment (LCA): Traditional LCAs capture and describe the environmental effects associated with a product, process or activity over its whole life cycle by calculating the material and energy requirements as well as emissions to air, water and soil and by assessing the related environmental consequences. An LCA comprises four major stages: goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation of the results (International Organization for Standardization, 2006). The goal phase defines the overall objectives of the study, i.e., what questions need to be answered. The scoping phase sets the boundaries of the system under study, the sources of data and the functional unit to which the achieved results refer. It is analogous to a scoping process for an ISA. The Life Cycle Inventory (LCI) consists of an eco-balance for the process or product being studied, i.e., a detailed compilation of all the environmental inputs (material and energy) and outputs (air, water and solid emissions) at each stage of the life cycle. These resource and input/output flows are comparable to the measures associated with indicators and attributes in SDH and OH (respectively).

As Miettinen and Hämäläinen (1997) point out, "the inputs and outputs are not interesting per se, but their potential environmental impacts are." Hence, the Life Cycle Impact Assessment (LCIA) phase aims at quantifying the relative importance of all environmental burdens obtained in the LCI by analysing their influence on selected environmental impact categories. In the next step of an LCA study, the results from the LCIA stage are aggregated into areas of concern, such as human health or climate change using a set of weights, sometimes derived using decision theoretic methods and in other cases based on management preferences. The areas of concern can also be aggregated to as to calculate a single score for an alternative. ISO deems both aggregation steps as optional. This branching arrangement is referred to as a value tree in the LCA literature.

Although they have been described in a different order, an LCA has stages that parallel the preceding hierarchies. All begin at the same point in the decision process with the articulation of a goal, e.g., minimize the environmental impacts such as contribution to global warming impact, or maximize contribution to sustainable development, of the mine or project. The scope of a study is determined by the problem or system boundary that is selected, which in turn depends upon which system elements are of concern, just as an SDH hierarchy identifies what is to be sustained and an OH identifies which objectives are relevant to the decision context. Although not normally stated as a rule or objective, scope is similar to an SDH principle or upper level objective. Areas of concern are comparable to criteria or mid-level objectives. Areas of concern are further subdivided into impact or mid-point categories such as acidification or global warming potential, which are comparable to indicators or attributes. Moreover, as noted above, the data collected during the LCI provides the measurement.

Comparing SDH, OH and LCA: The three processes described here have many characteristics in common, but also differences. All three can be used in phase I of an ISA-problem structuring and scope definition. All are applicable at multiple spatial scales, from the site- or process-specific scale to scales that span entire countries, regions of the world, or the global operations of a single firm. And as noted above, each is organized

as a hierarchy. The overall LCA process goes further than an SDH or OH in those cases where the LCIA scores are aggregated into areas of concern or a single score. Conversely, when an SHD or and OH is used in the problem framing phase of an ISA, the existence of succeeding steps for aggregating the lower elements to obtain scores for higher levels, is assumed but not necessarily discussed.

Table 1 compares levels across the three approaches. Depending upon the practitioners involved, there may be significant differences in the number of levels, how each level is defined and what label is attached. For example, what in SDH are called indicators, OH calls attributes and LCA calls mid-point categories. In LCA, the variables being measured are sometimes called species, areas of concern may be called damage categories or end-point categories, interventions, or even indicators and single point scores are sometimes called areas of concern. These are semantic differences; in all three cases the hierarchy descends from the general to the specific, from goals to actual measurements and those measurements can be aggregated in some manner to create a ranking score for a project alternative.

All three processes are applicable to both the public and private sectors, although SDHs are more commonly seen in government settings, while LCAs are more widely used in industrial and research settings. OH are found equally in both settings. This difference can in part be explained by considering the three in the context of a continuum that ranges from purely ethics-based decision making at one end to purely fact-based decision making at the other end.

Sustainability is an ethical construct that utilizes science to track progress toward societal goals. Thus SHDs reside nearer to the ethics-based end of the continuum. They are particularly well suited for ongoing sustainability assessments, such as those carried out by governments. For example, the U.S. Forest Service reports every ten years on a suite of indicators of sustainable forests and includes extensive stakeholder participation and review in the indicator revision, data analysis and reporting processes (United States Forest Service, 2010). The goal is to assess progress (or lack thereof) toward reaching a set of criteria describing various features of sustainable forests. Some ISA practitioners have suggested that SDH indicators cannot be predictive, because they are based on historic trend data. If that supposition is accepted, an ISA based on an SDH could only be used for contemporaneous or ex post assessments. Conversely, if indicators are designed to allow for trend extrapolation or some other form of forecasting, then an SDH could be the basis for an ex ante analysis.

Table 1: Comparison of sustainability hierarchy, objectives hierarchy and LCA value tree components

Sustainability hierarchy	Objectives hierarchy	LCA value tree
Goal	Strategic objective	Goal
Principles	Upper Level objectives	Scope
Criteria	Mid and lower objectives	Areas of concern
Indicators	Attributes	Mid-point categories
Measures	Measures	Attributes and measures

LCA is closer to the opposite end of the continuum. Goal setting is subjective in all cases and scoping can be subjective to the degree that system boundaries are chosen to intentionally include or exclude certain inputs or emissions, rather than for sound, defensible scientific or engineering reasons. Selection of environmental areas to address (or not) can also be highly subjective. For example, scientists at Utrecht University conducted an ex ante sustainability assessment of several technologies under development in the chemistry program (Roes and Patel, 2011). An LCA approach was taken, but only the mid-point categories of non-renewable energy use and climate change potential were estimated.

An LCI and much of the LCIA are objective activities. Inventory analysis is a mostly straightforward, if technically challenging, procedure where biological and engineering expertise from the multidisciplinary research team (always recommended when dealing with LCA) is used to identify energy, material balances and pollutant emissions. Assuming it has been done correctly and completely, an eco-balance is simply a statement of fact, or in the case of an ex ante assessment, a statement of estimations (predictions) presented in the form of probability distributions.

These objective results emerge as a long list of natural resource uses and emissions in air, water and soil that must be converted into understandable and meaningful indicators before practical use can be made of them. The next steps, classification and characterization, are used to calculate mid-point environmental impacts like Global Warming Potential (GWP). The classification step assigns items in the eco-balance inventory to one or more mid-point categories. The characterization step then quantifies the contribution of the item to the mid-point category value, for example the contribution of nitrates emissions to eutrophication.

Both steps are objective to the degree that they are based on environmental science regarding the effects of different substances in eco-systems; however, it is important to recognize that some relationships remain controversial or are only hypothesized. Three other caveats are necessary regarding characterization. Practitioners often use standard Life Cycle Impact

Assessment (LCIA) methods, such as Eco-indicator 99 (Goedkoop and Spriensma, 1999) or Impact 2002+ (Jolliet *et al*., 2003), which contain Characterization Factors (CF). However, scientific advancements may have been made since the CF was originally created; the CF may only be accurate for a specific type of ecosystem, one that is significantly different than the one existing at the project location; or the CF may not adequately deal with spatial or temporal variations from those utilized in its creation.

Because subjective input reenters the LCA process after characterization, International Organization for Standardization (2006) recommends that LCAs end with a set of mid-point environmental indicators, which provide a fairly objective and comprehensive, though not fully exhaustive, environmental picture of the system under study. Measures contributing to the mid-point category level can be traced back to the specific life cycle stage where they occur, which is useful for identifying the life cycle stage at which emissions or resource use is happening, a benefit that neither SDH nor OH can offer. These features make the LCA process well suited for supporting private sector decision making in ex ante, ongoing and ex post contexts. Its applicability beyond phase I of an ISA will be discussed in the next section.

Objectives hierarchies fall between these two extremes and may more closely resemble one of the preceding processes or the other, depending on how the OH has been constructed. If the OH was created collaboratively with stakeholders, and the value set underlying those objectives has strongly influenced which objectives are included and how the objectives are phrased, the approach will be similar to a sustainability hierarchy. Conversely, if the objectives are based on scientific criteria such as knowledge about the components and interactions of a functioning biophysical or engineering system or process, then the approach might look more similar to an LCA value tree. Each OH design will reflect the needs of the public or private sector user and its application to ex ante, ongoing or ex post ISA.

Multi-Criteria Decision Analysis Models (MCDA): In phase III of an ex ante project assessment alternatives are compared and ranked. Doing so is particularly challenging when the problem at hand is multi-faceted, the alternatives have both quantitative and qualitative aspects and each alternative will impact the firm and its stakeholders in different ways. An SHD, OH or LCA will contain an enormous amount of information for each alternative; however, decision makers in the firm and stakeholders, may not fully comprehend the implications of each separate indicator or the interactions among them. Moreover, it is difficult to keep track of each piece of information, each participant's preferences for individual objectives and the subtle differences between alternatives.

The purpose of Multi-Criteria Decision Analysis (MCDA) models is to combine various types of information from a multitude of sources so as to facilitate their interpretation as a whole. They can provide a transparent, replicable, auditable trail of phase III of the decision process, highlighting differences among alternatives and the implications for ranking of different preferences. As such, they are particularly useful in analysis and comparison of different scenarios.

There are numerous types of MCDA models, virtually all of which are quantitative, assume that problems can be structured in a logical manner and that decisions are based on a rational choice to maximize satisfaction. The techniques fall into two broad categories: optimization and multi-attribute decision analysis. We focus here on the latter, for two reasons. First, optimization models simultaneously maximize and/or minimize over a set of criteria or objectives, subject to a set of constraints. As such, they are more useful for operational decisions, such as design choices where social and environmental impacts are comparable across alternatives and where there is a single decision maker and direction of preference, than they are in multi-stakeholder situations (Azapagic and Perdan, 2005a; b). Conversely, multi-attribute approaches are well suited to situations involving multiple players with differing directions of preference and risk tolerance. Second, multi-attribute methods allow for aggregation of indicators at each succeeding level of a hierarchy (Belton and Stewart, 2002), which is useful in sensitivity analyses. They are also useful for regional sustainability assessments (Boggia and Cortina, 2010).

Multi-attribute models associate a real number or score with a project alternative. They are compensatory, meaning that weak performance on one indicator can be compensated for by strong performance on another, which can be a weakness in cases where a poor score on a specific attribute would be unacceptable. LCAs are also compensatory. Weighting is an integral, rather than discretionary, component. One of the most common forms of multi-attribute model derives from Multi-Attribute Value Theory (MAVT) (Keeney and Raiffa, 1993). A simple additive MAV function takes the form:

$$V(a)_m = \Sigma\, w_{km}\, v_{km}(a) \quad k = 1,\ldots K$$

The value of alternative a for stakeholder m is the weighted sum of the value functions for each of the K

indicators associated with a, where w_{km} is the weight assigned to the k^{th} indicator by stakeholder m and $v_{km}(a)$ is the value function associated with the k^{th} indicator for stakeholder m. The weight represents how important a specific indicator is, relative to all the other indicators. The value function quantifies an individual's perception of the seriousness of a change in an indicator's level. A downward sloping value function indicates that less of what the indicator measures is better and upward sloping indicates the opposite. Linear value functions are risk neutral, concave value functions indicate risk seeking behavior and convex ones indicate risk aversion. A multi-attribute utility function (MAU) differs from a MAV function in that uncertainty about outcomes can be incorporated into the model, making them useful in situations where outcomes of alternatives are uncertain, a common situation when dealing with complex problems and ex ante analyses. For the sake of simplicity, we will focus on MAV functions.

RESULTS AND DISCUSSION

SDH, OH and LCA can each be used by themselves. For example, an SDH or an OH could be used simply as a platform for social learning, information transfer, or as the basis for a non-quantitative comparison of alternatives. LCAs are also frequently conducted as stand-alone analyses. Conversely, aspects of one of the aforementioned tools could be imported into or inform another. For example, the structure of an LCA value tree, e.g., the selection of mid-point categories, could reflect the results of an SDH or OH, or vice versa. Or, the structure of an OH could reflect knowledge gained during a prior full or streamlined LCA.

Some approaches are based on tools that had a specific purpose, e.g., LCA, but the scope of which is now being expanded, e.g., by including social measures in an LCA. The U.N. Environmental Programme has published a methodology for incorporating 31 subcategories into a social life cycle assessment. They do not provide guidance on aggregating subcategory indicators or on characterization, or interpretation (Benoît-Norris *et al*., 2011). This is a relatively new field for which the peer reviewed literature is sparse (Jørgensen *et al*., 2008), but which nonetheless shows promise.

Another example of merging disciplines is the use of decision theoretic tools rather than expert judgment to assign the LCA weights. For example, Seppälä (2001) developed a framework for decision analytic impact assessment in which a value tree of mid-point categories and associated attributes (and measures), forms the basis for an LCA. The weights used to calculate the areas of concern (damage categories) and final score were assigned based on decision theoretic principles. Alternatives are assigned an impact score by summing the weighted attributes in a manner consistent with multi-attribute value theory techniques, though value functions are not used. Miettinen and Hämäläinen (1997) took a similar approach. They developed an LCA based on a set of impact categories and associated attributes. They then showed how it could be embedded in a value tree that describes a project (or in their case policy problem) for which the environmental assessment was conducted. However, rather than using MCDA to analyze the entire value tree, they assigned linear (risk neutral) value functions to only the environmental portion of the tree and aggregated using an additive MAV function.

Other approaches are based on using MCDA models, which are populated with data derived from various tools, including LCA, but which restrict each underlying tool to its original purpose, e.g., environmental or economic analysis. Azapagic and Perdan (2005a; b) fall into this second category. They developed a decision framework that lays out a series of stages that resemble the initial phases of an ISA: stakeholder engagement, problem definition, design of alternatives, identification of decision criteria and elicitation of preferences over those criteria. The authors recommend organizing decision criteria into a value tree. Data for indicators comes from other models and tools. They then describe a variety of multi-criteria techniques that can be used to weight the indicators and compare alternatives (phase III). Other authors have taken a similar approach, integrating LCA and other model outputs into some form of MCDA model (Dey, 2006; Hermann *et al*., 2007; White *et al*., 2006).

To further inform our discussion on the strengths and weaknesses of using a combination of methods, an illustration of a value tree for a LCA applied to a hypothetical quarry is presented in Fig. 3. Such a value tree is adapted from the Impact 2002+ LCIA method (Jolliet *et al*., 2003). The mid-point categories reside in the center of the figure and are linked on the right to attributes, which are in turn linked to the life cycle stages. To the left, mid-point categories are aggregated into damage categories (areas of concern), which are then aggregated into a single score index. The mid-point category values are created through classification and characterization of the inventory of attributes, an objective process. Conversely, some form of subjective weighting is required to calculate the damage category and single score index values, which is shown in the latter case.

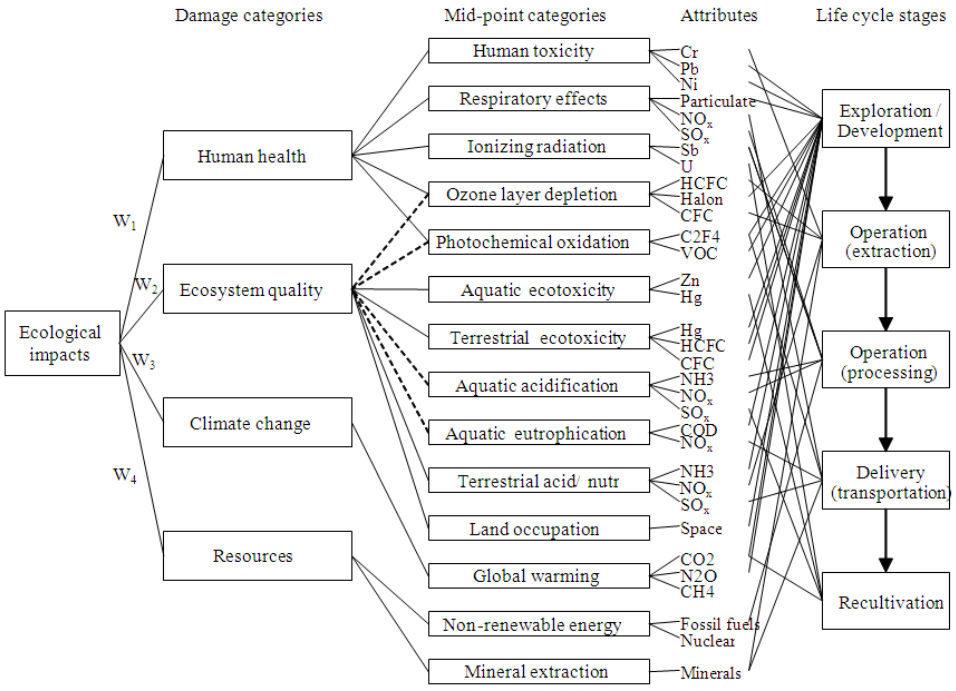

Fig. 3: LCA value tree for aggregates quarrying

As noted previously, an LCA stopped after the characterization step is fairly objective. The deliverable at this stage is the eco-profile, summarized by the values obtained for each mid-point category indicator. Similarly, SDH indicators and OH attributes are objective, assuming they have been selected and populated with data in a manner consistent with accepted scientific methods. Decision maker(s) can see the eco-profile mid-point category information as background knowledge, combining it with complementary information that has not been included in the LCA to make a decision.

Unfortunately, decision makers too often are unable to understand and fully exploit the results of an LCIA. They may lack the technical knowledge to understand the implications of results. Or in cases where LCIA is being used to compare a set of alternatives, the mid-point category scores may not point to a single definitive choice that is the 'best', i.e., the least environmentally damaging, system. One alternative may be better with respect to global warming potential, while another is better with respect to ecotoxicity. When this occurs, the decision maker is forced to make trade-offs, to decide which mid-point category indicators are more important in the given circumstance and which are less so.

To assist in the process, the valuation step in LCA uses numerical weights based on preferences (value choices) to create first the areas of concern (damage category) values and then a unique indicator for the single score index. Conceptually, the mathematical function used to calculate the score is comparable to a MAV function (Seppälä *et al*., 2001).

There is neither consensus on weighting, nor on the best valuation method to be adopted (Reap *et al*., 2008a; b). Some efforts have been made to create a standardized weighting scheme, one of which is Eco-Indicator 99 (Goedkoop and Spriensma, 1999). The weakness of such approaches is that the weighting parameters are not site, situation, or community specific. More recently Ahlroth and Finnveveden (2011) have developed a new weighting set titled Ecovalue08, where they used Willingness To Pay (WTP) estimates of environmental quality and market values for resource depletion. WTP is a powerful tool when applied correctly (Champ *et al*., 2003), but results will necessarily differ across cultures and regions, so Ecovalue08 will not be universally applicable. Further, market prices for minerals are recognized to be poor indicators of long-term resource scarcity, as differentiated from situational scarcity (Shields and Šolar, 2011; Svedberg and Tilton, 2006). An alternative approach is to select the weights using the methods developed in MCDA.

To base an ISA on an LCA, variables for social and economic issues need to be included in the value tree

(Pennington *et al*., 2004). There are, however, a number of challenges. Care needs to be taken during the design phase to ensure that the full range of sustainability issues have been included. This could be accomplished by preceding the LCA step with either an SDH or an OH, or adaptation of the UN social LCA method, which in its current form is not entirely appropriate for mining development. There would also need to be balance across social, economic and environmental areas, because areas more fully explicated (the environmental aspects that LCA practitioners are confident about, for example) may be over represented and thus unintentionally given greater weight than other areas. Further, some social indicators are qualitative and some economic indicators are not additive and so cannot be aggregated as are traditional LCA indicators (Kruse *et al*., 2009).

LCA is a compensatory technique; poor scores on selected indicators could in theory be offset by good scores on others. Nonetheless, LCA is largely a technique to look at damages, whereas an ISA must address both costs and benefits of alternatives and be sensitive to whom they accrue. For these reasons, we recommend that the second approach be taken, i.e., LCAs be used to create the eco-profile which is then passed forward to a MCDA.

As noted previously, one of the core principles of sustainability and an essential component of an ISA is stakeholder engagement. Stakeholders have a right to information about governmental or industry actions that have the potential to impact their lives, community or health. They also should have the right to express their opinions about those actions. Too often in the past decisions within the minerals industry were made without transparency and were based solely on the preferences of the firm or the firm's management. Even authors who recommend using MCDA techniques, such as Azapagic and Perdan (2005a; b) and (Seppälä *et al*., 2001), speak only about basing weights on the preferences of the decision makers. However, starting with goal definition in phase I and moving forward through the ISA process, stakeholders have concerns that need to be acknowledged and addressed. They may well want issues included in the analysis that would not otherwise be considered by the firm.

For example, when siting a construction and demolition waste disposal facility a firm typically focuses on technical and environmental issues, but nearby neighbors may be much more concerned about land occupation, such as changes to their view-shed or disruption of community activities due to traffic or noise. Firms also focus on technical and environmental issues when siting tailings disposal sites, but neighbors may be more concerned about impacts on traditional hunting areas or indigenous sacred sites. Thus, as illustrated in Fig. 1, the authors believe that an ISA must start with identification of stakeholders and their objectives, organized into either a SDH or an OH so as to make their connections to subsequent indicators or mid-point categories clear.

Once alternatives (scenarios) have been created that address the full range of stakeholder objectives (phase II), technical, economic, social and environmental review takes place, in each case using the best available tools. In phase III scores are calculated and alternatives compared. MCDA models can provide a framework within which the output from all the tools utilized can be incorporated because such models can accommodate both qualitative and quantitative data generated from other tools (once they are all normalized). The firm might use DCFROR analysis to estimate financial flows, an LCA to estimate environmental impacts, an input-output model to calculate indirect and induced income in affected communities, or perhaps even a computable general equilibrium model to further clarify economic interactions, and public health data to incorporate the presence of populations whose health could be excessively impacted by certain types of emissions. Results are then fed into the overarching MCDA.

Choosing a single weighting scheme, one that is acceptable to all parties, can become so politically fraught that no attempt is made to calculate scores for ranking. An alternative approach is to run the MCDM multiple times using the preference-based weights and value functions of the decision maker and then those of each major stakeholder group. This step is crucial as it is a direct acknowledgement of the firm's concern about the views of others. Different parties will assign greater or lesser weight to different aspects of the project, e.g., some stakeholders will place more weight on land occupation than do other participants. Perhaps more importantly, risk preference information can be captured in the value functions. Engineers and scientists think differently about risk than do stakeholders who lack a technical education. There are numerous instances in which community opposition to a mineral development has stemmed from misunderstandings about the magnitude and distribution of risk.

Once the model is fully developed, with weights and value functions determined, numeric scores can be calculated for each indicator for each interested party. This matrix of weighted data clearly shows the relative importance of various indicators for each stakeholder. These data can then be combined using an MCDA function, with the scores reported for each level of increasing aggregation, for each stakeholder, again clearly showing the effects of differences in values, preference ranking and risk tolerance.

One stakeholder might score the firm's preferred alternative very low. By examining the weighted indicators and aggregated scores and also going back to base information such as life cycle stage of the LCA, it will be possible to identify exactly which aspects of a project the stakeholder finds troubling. That information can form the basis for discussions on how the project could be modified to assuage their concerns. Another benefit of this approach is that having asked various stakeholders about their objectives and preferences and having shared what they report with all participants and used them in the ISA process, each stakeholder then publicly 'owns' their position. For example, one stakeholder might prefer an alternative disposal site that is further from their home, but then must also recognize that the alternative location will require longer haul distances with attendant emissions of green house gasses.

CONCLUSION

Sustainable development is not a destination; it is an ongoing journey that must be supported by knowledge, social learning and adaptation. Decisions made in the context of sustainability are likewise part of an ongoing process. The linear, partial equilibrium decision methods used in the past to compare alternatives and support decision making are no longer adequate to capture the complex issues and trade-offs that must be made. Rather, decisions should be supported by an ISA, beginning ex ante, continuing over the life of the project and ex post as well.

In this paper we have focused on ex ante assessments, those undertaken prior to investment. We have identified a subset of tools that can support an ISA. SDH, OH and LCA have features in common, e.g., they provide a framework within which to organize objectives and link them to indicators. All acknowledge the subjective, value basis of their structure; weights can be assigned to the indicators or mid-point categories and to the intermediate and upper levels of each hierarchy.

Because the methods for incorporating qualitative and non-additive variables into LCAs is not yet adequately developed, we recommend structuring an ISA hierarchy as an SDH or OH, the environmental component of which could initially be designed as an LCA. Moreover, because handling the subjective components of an LCA continues to be debated, we recommend stopping an LCA after calculating the eco-profile, i.e., the values obtained for each mid-point category indicator. In an ex ante context this will fully exploit the potential of the methodology.

The data requirements for LCA are huge and for minerals projects must be site specific. Generic data has the potential be misleading and result in inappropriate or inconsistent conclusions (Reid *et al*., 2009; Van Zyl, 2005). Unfortunately, adequate information is often unavailable at the early design stage. One way to take advantage of LCA in an ex ante ISA is to take into account data uncertainty relevant to every activity in the life cycle, i.e., create a probabilistic inventory dataset.

For phase III of an ISA we recommend using MCDA, in the case of a probabilistic model, a multi-attribute utility function, rather than performing the analysis within an expanded LCA. MCDAs handle qualitative and quantitative data. Furthermore, risk communication is an important aspect of a multi-stakeholder ISA and the value functions embedded in a MCDA can capture and communicate risk preference.

In conclusion, no single tool can adequately support an ISA, but rather multiple tools are necessary, with each used in a manner consistent with its strengths.

REFERENCES

Ahlroth, S. and G. Finnveden, 2011. Ecovalue08-A new valuation set for environmental systems analysis tools. J. Cleaner Produc., 19: 1994-2003. DOI: 10.1016/j.jclepro.2011.06.005

Allenby, B.R., 2011. The Theory and Practice of Sustainable Engineering. 1st Edn., Prentice Hall PTR, Upper Saddle River, NJ., ISBN: 0132127997, pp: 432.

Azapagic, A. and S. Perdan, 2005a. An integrated sustainability decision-support framework Part I: Problem structuring. Int. J. Sustainable Dev. World Ecol., 12: 98-111. DOI: 10.1080/13504500509469622

Azapagic, A. and S. Perdan, 2005b. An integrated sustainability decision-support framework Part II: Problem analysis. Int. J. Sustainable Dev. World Ecol., 12: 112-131. DOI: 10.1080/13504500509469623

Belton, V. and T.J. Stewart, 2002. Multiple Criteria Decision Analysis: An Integrated Approach. 1st Edn., Springer, Boston, ISBN: 079237505X, pp: 372..

Benoît-Norris, C., G. Vickery-Niederman, S. Valdivia, J. Franze and M. Traverso et al., 2011. Introducing the UNEP/SETAC methodological sheets for subcategories of social LCA. Int. J. Life Cycle Assess., 16: 682-690. DOI: 10.1007/s11367-011-0301-y

Boggia, A. and C. Cortina, 2010. Measuring sustainable development using a multi-criteria model: A case study. J. Environ. Manage., 91: 2301-2306. DOI: 10.1016/j.jenvman.2010.06.009

Bohunovsky, L. and J. Jäger, 2008. Stakeholder Integration and Social Learning in Integrated Sustainability Assessment. SERI Sustainable Europe Research Institute.

Champ, P.A., K.J. Boyle and T.C. Brown, 2003. A Primer on Nonmarket Valuation. 1st Edn., Springer, Dordrecht, ISBN: 1402014457, pp: 576.

Conklin, E.J., 2005. Dialogue Mapping: Building Shared Understanding of Wicked Problems. 1st Edn, Wiley, Chichester, ISBN: 978-0470017685, pp: 264.

Darner, D., 2003. Die Logik des Misslingens: strategisches Denken in komplexen Situationen. 5th Edn., Rowohlt, Reinbek bei Hamburg, ISBN: 3499615789, pp: 346.

Dey, P.K., 2006. Integrated project evaluation and selection using multiple-attribute decision-making technique. Int. J. Produc. Econ., 103: 90-103. DOI: 10.1016/j.ijpe.2004.11.018

Finnveden, G., M. Nilsson, J. Johansson, A. Persson and A. Moberg et al., 2003. Strategic environmental assessment methodologies-applications within the energy sector. Environ. Impact Assess. Rev., 23: 91-123. DOI: 10.1016/S0195-9255(02)00089-6

Goedkoop, M. and R. Spriensma, 1999. The Eco-Indicator 99: A Damage Oriented Method for Life Cycle Impact Assessment. 2nd Edn., PRé, Product Ecology consultants, Den Haag, pp: 132.

Graedel, T.E. and B.R. Allenby, 2010. Industrial ecology and sustainable engineering. 1st Edn., Prentice Hall, Upper Saddle River, ISBN: 0136008062, pp: 403.

GRI, 2009. What is th mining and metals sector supplement. Global Reporting Initiative.

Hermann, B.G., C. Kroeze and W. Jawjit, 2007. Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators. J. Cleaner Produc., 15: 1787-1796. DOI: 10.1016/j.jclepro.2006.04.004

International Organization for Standardization, 1998. Environmental management: Life cycle assessment, Part 3: Life cycle impact assessment. 1st Edn., ISO, Geneva, pp: 33.

IVM/IES, 2006. SustainabilityA-Test. Institute for Enviornment Studies.

Jager, J. and L. Bohunovsky, 2008. Methods and Tools for Integrated Sustainability Assessment: Project Summary. Sustainable Europe Research Institute.

Jolliet, O., M. Margni, R. Charles, S. Humbert and J. Payet et al., 2003. IMPACT 2002+: A new life cycle impact assessment methodology. Int. J. Life Cycle Assess., 8: 324-330. DOI: 10.1007/BF02978505

Jørgensen, A., A. Le Bocq, L. Nazarkina and M. Hauschild, 2008. Methodologies for social life cycle assessment. Int. J. Life Cycle Assess., 13: 96-103. DOI: 10.1065/lca2007.11.367

Keen, M., V.A. Brown and R. Dybal, 2005. Social learning in Environmental Management: Towards A Sustainable Future. Earthscan, London, ISBN: 1844071820, pp: 270.

Keeney, R.L. and H. Raiffa, 1993. Decisions with Multiple Objectives: Preferences and Value Tradeoffs. Cambridge University Press, Cambridge, ISBN: 0521438837, pp: 569.

Kogel, J.E. , N.C. Trivedi, J.M. Barker, 2006. Industrial Minerals and Rocks: Commodities, Markets and Uses. 7th Edn., SME, Littleton, ISBN: 0873352335, pp: 1548.

Kruse, S., A. Flysjö, N. Kasperczyk and A.J. Scholz, 2009. Socioeconomic indicators as a complement to life cycle assessment-an application to salmon production systems. Int. J. Cycle Assess., 14: 8-18. DOI: 10.1007/s11367-008-0040-x

Lammerts van Bueren, E.M. and E.M. Blom, 1997. Hierarchical Framework for the Formulation of Sustainable Forest Management Standards: Principles, Criteria, Indicators. 1st Edn., Tropenbos Foundation, Netherlands, ISBN-10: 9051130317, pp: 82.

Miettinen, P. and R.P. Hämäläinen, 1997. How to benefit from decision analysis in environmental life cycle assessment (LCA). Eur. J. Operat. Res., 102: 279-294. DOI: 0.1016/S0377-2217(97)00109-4

Moon, D., S. Jeck and C. Selby, 1998. Elements of a Decision Support System: Information, Model and User Management. In: Multiple Objective Decision Making for Land, Water and Environmental Management. (El-Swaify, S.A. and D.S. Yakowitz (Eds.). Lewis Publishers, Boca Raton, ISBN: 1574440918, pp: 323-334.

O'Connor, M., 2006. The "Four Spheres" framework for sustainability. Ecol. Complexity, 3: 285-292. DOI: 10.1016/j.ecocom.2007.02.002

Payet, A., 2003. The Equator principles: A True Milestone in the Approach of the Banking Community in Project-Financing? How Environmental and Social Concerns Pervaded the Banking Perception of Project-Financing. 1st Edn., University of Essex, Essex, pp: 128.

Pennington, D.W., J. Potting, G. Finnveden, E. Lindeijer and O. Jolliet et al., 2004. Life cycle assessment Part 2: Current impact assessment practice. Environ. Int., 30: 721-739. DOI: 10.1016/j.envint.2003.12.009

Petrie, J., B. Cohen and M. Stewart, 2007. Decision support frameworks and metrics for sustainable development of minerals and metals. Clean Technol. Environ. Policy, 9: 133-145. DOI: 10.1007/s10098-006-0074-3

Rapport, D., 2003. Managing for Healthy Ecosystems. 1st Edn., Lewis Publishers, Boca Raton, ISBN: 1566706122, pp: 1510.

Reap, J., F. Roman, S. Duncan and B. Bras, 2008a. A survey of unresolved problems in life cycle assessment Part 1: goal and scope and inventory analysis. Int. J. Life Cycle Assess., 13: 290-300. DOI: 10.1007/s11367-008-0008-x

Reap, J., F. Roman, S. Duncan and B. Bras, 2008b. A survey of unresolved problems in life cycle assessment Part 2: impact assessment and interpretation. Int. J. Life Cycle Assess., 13: 374-388. DOI: 10.1007/s11367-008-0009-9

Reid, C., V. Bécaert, M. Aubertin, R. K. Rosenbaum and L. Deschênes, 2009. Life cycle assessment of mine tailings management in Canada. J. Cleaner Produc., 17: 471-479. DOI: 10.1016/j.jclepro.2008.08.014

Roes, A. L. and M. K. Patel, 2011. Ex-ante environmental assessments of novel technologies-improved caprolactam catalysis and hydrogen storage. J. Cleaner Produc., 19: 1659-1667. DOI: 10.1016/j.jclepro.2011.05.010

Saaty, T.L., 1990. The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. 1st Edn., McGraw-Hill International Book Co., New York, ISBN: 0070543712, pp: 287.

Seppälä, J., L. Basson and G.A. Norris, 2001. Decision analysis frameworks for life-cycle impact assessment. J. Indust. Ecol., 5: 45-68. DOI: 10.1162/10881980160084033

Shields, D., S.V. Šolar and W.E. Martin, 2002. The role of values and objectives in communicating indicators of sustainability. Ecol. Indicators, 2: 149-160. DOI: 10.1016/S1470-160X(02)00042-0

Shields, D.J. and S.V. Šolar, 2004. Sustainable Mineral Resource Management and Indicators: Case Study Slovenia. 1st Edn., Geological Survey of Slovenia, Ljubljana, ISBN: 9616498037, pp: 84.

Singh, R.K., H.R. Murty, S.K. Gupta and A.K. Dikshit, 2009. An overview of sustainability assessment methodologies. Ecol. Indicators, 9: 189-212. DOI: 10.1016/j.ecolind.2008.05.011

Stock, P. and R.J.F. Burton, 2011. Defining terms for integrated (multi-inter-trans-disciplinary) sustainability research. Sustainability, 3: 1090-1113. DOI: 10.3390/su3081090

Svedberg, P. and J.E. Tilton, 2006. The real, real price of nonrenewable resources: copper 1870-2000. World Develop., 34: 501-519. DOI: 10.1016/j.worlddev.2005.07.018

Van Zyl, D.J.A., 2005. Towards Improved Environmental Indicators for Mining Using Life Cycle Thinking. In: Life Cycle Assessment of Metals: Issues and Research Directions, Dubreuil, A., (Ed.). Society of Environmental Toxicology and Chemistry (SETAC), Pensacola, ISBN: 1880611627, pp: 117-122.

Von Winterfeld, D. and W. Edwards, 1986. Decision Analysis and Behavioral Research. 1st Edn., Cambridge University Press, Cambridge, ISBN: 0521273048, pp: 604.

Wallis, A.M., A.R. Kelly and M.L.M. Graymore, 2010. Assessing sustainability: A technical fix or a means of social learning? Int. J. Sustainable Develop. World Ecol., 17: 67-75. DOI: 10.1080/13504500903491812

Weaver, P.M. and J. Rotmans, 2006. Integrated sustainability assessment: What is it, why do it and how? Int. J. Innovation Sustainable Develop., 1: 284-303. DOI: 10.1504/IJISD.2006.013732

White, S., S. Fane, D. Giurico and A. Turner, 2006. Putting the economics in its place: decision making in an uncertain environment. Proceedings of the 9th Biennial Confernce of the International Society for Ecological Economics, Dec. 15-18, New Dehli, pp: 1-26.

Zopounidis, C. and M. Doumpos, 2002. Multicriteria classification and sorting methods: A literature review. Eur. J. Operat. Res., 138: 229-246. DOI: 10.1016/S0377-2217(01)00243-0