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Application of multi-criteria decision analysis in design of sustainable environmental management system framework

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ABSTRACT

Proactive environmental management initiatives such as pollution prevention, cleaner production and sustainability are inherently multi-objective processes that require joint considerations of environmental, industrial, economic and social criteria in all stages of decision making. The success of such initiatives, however, depends on the solidity and the relevance of their strategic frameworks. This paper proposes strategic positioning of pollution prevention and clean production projects via design of a sustainable environmental management system (SEMS) that is responsive to regulatory requirements, and is relevant to industry culture and business structure. Built on the traditional and familiar environmental management system platform and the requirements of the multi-criteria decision making models ELECTRE III, the SEMS is capable of supporting design and implementation of defensible solutions to environmental problems industry face today according to sustainability criteria. The ELECTRE III model was selected as an integral part of the framework due to its ease of application, flexibility in design and selection of performance criteria, and capability to identify the best management solutions by giving an order of preference to multiple alternatives. The proposed SEMS framework is also in line with the Rio+20 sustainable development goals, objectives and guidelines that call for action and result-oriented strategies and institutional frameworks that could account for multiple stakeholders' key issues while suggesting environmental solutions according to the three dimensions of sustainable development. A case study that demonstrates the management of waste streams at a manufacturer of energy drinks and diet bars is provided to demonstrate how the SEMS can be designed and implemented.

1. Introduction

The techniques used in environmental management have evolved over time. In the 1970s and 1980s the focus was on controlling significant pollution problems through regulation, standards, and assigning control mechanisms. The concept of Cleaner Production (CP) was introduced by the United Nation Environmental Programme (UNEP) Industry and Environment in 1989 as an integrated preventive environmental strategy with anticipated impact on reducing environmental and ecological risks (*via increasing eco-efficiency, conservation of raw materials and energy, elimination of toxic emissions, reducing negative impact of the product life cycle, and including environmental concerns into services-a sustainable consumption and production approach*). The pollution prevention (P^2) programs and initiatives implemented in North America soon after followed the CP format focusing on reducing and/or eliminating waste at the source (*through modification of production processes, promotion of the use of non-toxic or less-toxic substances, implementation of conservation techniques, and re-use of materials rather than putting them into the waste streams*). Both the CP and P^2 initiatives offered design of continuous integrated preventative environmental strategies that could apply to processes, products, and services in order to increase the overall efficiency and reduce risks to humans and the environment (UNEP, 2001; Grutter and Egler, 2004).

The inclusion of economic and social criteria, and the need for the involvement of multiple stakeholders in strategic planning for environmental protection was initiated in the early 1990s and have resulted in the development of more proactive environmental management programs. These initiatives aimed at securing environmental and economic sustainability and emergence of voluntary and market-based programs that are growing in popularity today.

Abbreviations: Sustainable environmental management system, (SEMS); Environmental management system, (EMS); Multi-criteria decision analysis, (MCDA); Triple Bottom Line, (TBL); Accounting, Global reporting initiative, (GRI); Sustainability cost accounting, (SCA).

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To assist with the implementation of the CP/P^2 initiatives, in the mid 1990s the International Organization for Standardization proposed the ISO 14000 standards. In the United States, a similar approach was pursued and USEPA introduced design and implementation of environmental management systems (EMS) through which organizations could systematically assess, monitor, track and address their pollution, resource usage and impact on the environment (negative environmental externalities). These efforts were accompanied by a family of other environmental strategies and guidelines proposed by the European Commission, World Business Council for Sustainable Development, UNEP, other ISO standards (i.e. ISO 26000), Guidelines on Social Responsibility, Triple Bottom Line (TBL) Accounting, The Global Reporting Initiative (GRI), and the OECD guidelines for multinational enterprises) (Khalili, 2011).

The advantage of an environmental management system is that it can provide a consistent, yet customized approach to the design of environmental monitoring, regulatory compliance, pollution prevention, and design of clean production programs across the whole supply chain. The key steps presented in traditional EMS design include setting management goals and policy; creating an EMS team; characterizing operations; collecting and analyzing data; assessing environmental aspects of the operations and activities; developing solutions to address those aspects followed by their implementation, review, and modification, if and as needed.

Environmental management strategies today, however, are charged with design and implementation of integrated approaches that can ensure sustainability- that is, emphasizing the reduction of industrial pollution and its negative impacts on the environment, economy and society. It is no secret that today the concept and the application of sustainability have gained tremendous momentum from legislative, social, cost efficiency, and even business survival perspectives. A multitude of terms, techniques and frameworks have been developed and proposed to assist organizations with designing and pursuing their sustainability goals, objectives and initiatives. Understanding these various terminologies and how they fit together, however, can be overwhelming in and of itself, not to mention devising a viable strategy for pursuing sustainability.

The need for advancing CP/P^2 programs to include sustainability in organizations' strategic framework has been documented by many authors. As an example, Kjaerheim, 2005, suggested that the intangible benefits and human factors derived from clean production projects need to be addressed by investigating how current CP/P^2 models may be improved and how their concept can be expanded to more directly address sustainability concerns (i.e. impact of industry on human health, creating job opportunities, eradicating poverty, and improving safety) (Kjaerheim, 2005). If designed and implemented successfully, a sustainable CP/P^2 program should be able to address social, economic and environmental goals simultaneously and in a quantifiable manner.

Fig. 1 presents a simplified overview of the evolution of environmental management programs and the need for the development of an SEMS to assist with building sustainability projects within the existing environmental management initiatives such as those identified in the CP/P2 programs.

In continuation of recent advances and efforts to include sustainability goals and objectives in environmental management strategies, this paper proposes a methodology for design of sustainable environmental management systems as a framework for materializing sustainability efforts in a comprehensive industry-specific manner. The proposed SEMS can be used to direct organizations' efforts toward designing products, formulating operations, and modeling their supply chain according to a well defined set of goals and performance criteria that are in agreement with the industry's perceived impacts on the social, economic, and environmental systems within which they are operating. As explained in the following sections, the SEMS framework also includes guidelines for design of internal operational initiatives, and external collaborative efforts that support overall profitability while addressing sustainability at every institutional level.

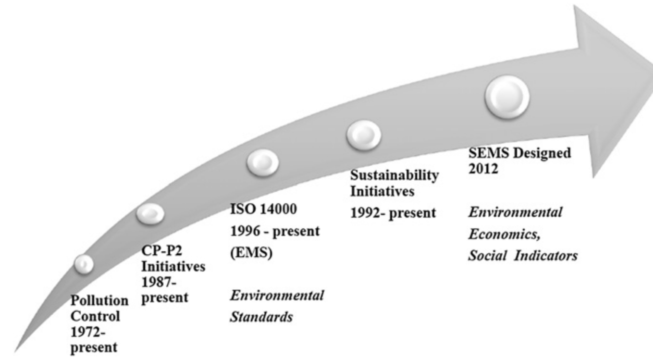

Fig. 1. Evolution of environmental management systems according to developmental goals and objectives.

2. Design of the sustainable environmental management system (SEMS)

This paper proposes a methodology for design of sustainable environmental management system (SEMS) frameworks to support sustainable operations and interdependencies among strategic, business, and manufacturing plans. It also responds to the growing need for utilizing decision-making guidelines that are specific to the management of environmental pollution in a sustainable manner.

The SEMS is a customized environmental management strategic planning tool for sustainability; it requires and directs development of specific economic, environmental, and social criteria in line with the organization's goals, and those of its internal and external stakeholders. The framework requires establishment of performance criteria and associated indicators to serve as input parameters to the decision-making model ELECTRE III. This model is selected because it has the capability of ranking and prioritizing environmental pollution prevention (or control) options according to their sustainability scores.

The SEMS framework is designed based on the familiar EMS platform; as such, it can be easily adopted, configured and customized to meet sustainability goals and objectives of organizations pursuing waste minimization, process optimization, or improvements in process efficiency and energy use. The SEMS can be also be used to develop environmental management solutions that are specific to and supportive of the organization's culture, business model and developmental goals. The similarities and differences of the EMS and SEMS frameworks are presented in Table 1a and b. As shown modifications to the EMS framework included:

- Changing the "EMS Team" structure, format, function, and responsibilities according to the requirements identified by the selected multi-criteria-decision-analysis (MCDA) model ELECTRE III that requires involvement of the principal decision makers (DMs), and multiple internal and external experts and stakeholders starting in the early stages of the SEMS design.
- Charging the SEMS team with responsibility to develop a set of performance criteria and associated indicators to assist with evaluating, and understanding the current state of the organization's performance, its strategic plan and direction, and the gap between the current and desired levels of performance

Table 1
A comparison between EMS and SEMS framework.

Design steps	Definition	EMS	SEMS
1-Set goals and objectives	The objective of this step is to develop a set of measurable goals, objectives and criteria that can lead a company towards the ultimate goal of reducing their negative externalities. This first step is crucial as it provides direction, focus and priority(ies).	Waste characterization, reduction goals and objectives: reducing negative environmental aspects	Waste characterization, and reduction goals and objectives as well as selection of performance criteria in economic and socially acceptable fashion: reducing environmental aspects in the most acceptable economic, and social manners
2-Develop policy	The objective of this step is to develop a "policy" that states the company's commitment to addressing environmental aspects and impacts of operations.	Environmental policy maximizing waste reduction and environmental benefits	Sustainability policy focusing on maximizing cumulative environmental, economic, and social benefits
3-Design the team	The ideas within the policy may be generated by collecting input from a management team put together by the EMS champion.	EMS team consists of internal stakeholders focusing on managing environmental aspects of operation	SEMS team consists of internal and external 1 stakeholder and decision makers, focusing on managing operations environmental aspects considering economics and social factors and the impacts.
4-Design process/operation and audit programs	The objective of this step is to comprehensively identify and document information on the industry/operation. Walk through. Manual data collection, review of reports. Modeling efforts	Evaluate sources, types, characteristics, and environmental aspects/impacts of emissions	Evaluate sources, types, characteristics, and environmental, economics, and social impacts of operations and emissions using a system approach.
5-Collect data	The objective of this step is to collect detailed data, in context of the defined goals and objectives. The types of tools used vary across companies in their platform, sophistication, and integration with other business functions (Mendoza, and Prabhu, 2003b).	Collect data on environmental emissions (sources, types, characteristics)	Collect data for operations: using a "system approach" focusing on, material, energy, water use, environmental emissions (wastes), in addition to operation/process efficiency, potential data on the economics/social impacts of the operations and wastes.
6-Assess data: aspect analysis	Data analysis focuses on qualitative and quantitative assessment of the environmental aspects of operations.	Develop and record environmental aspects of operation (base case scenario).	Develop. record environmental. economic, and social aspects of the operation (base case scenario).
7-Assess Data Impact Analysis	Data analysis focuses on qualitative and quantitative assessment of the Environmental Impacts of the operations.	Evaluating Environmental Impacts of Operations as is (base case Scenario).	Evaluating Environmental. Economic, and Social Impacts of the operation as is (the base Case Scenario).
8-Design and characterize environmental management Solutions	Develop and document emission management strategies according to the developed goals and objectives of waste minimization, as stated in environmental policy. Solutions may be short-term or long-term. Economic factors are a significant component in the selection of a solution (Tisdell, 1996).	Design strategies for emission elimination/reduction via (P2/CP), and/or control, and estimate their efficiency, effectiveness, benefits and costs.	Design strategies for emission elimination/reduction via (P2/CP), and/or control followed by a quantitative and qualitative assessment of their integrated impact on environmental. economic, and social dimensions using pre-selected criteria and indicators by the SEMS team utilizing MCDA (i.e. ELECTREIII) models. develop performance criteria. indicators, weights and thresholds associated with defined by the SEMS team.
9-Select solutions	The purpose of this step is to identify the most effective and economical solution.	Companies should explore a number of potential waste management strategies and select the one that is most cost-effective	Companies should explore a number of potential waste management strategies. assess and rank those according to their cumulative impact defined by an environmentally/economically/socially weighted score.
10 Implement solutions	The purpose of this step is to put in place the solutions by implementing project(s) selected in Steps 8–9	Implement the most cost effective strategy	Implement the most sustainable strategy defined via ranking scores
11 Evaluate solutions	The purpose of this step is to evaluate if implementation of the selected waste management strategies resulted in meeting desired/stated environmental management goals and objectives stated in the policy statement.	Evaluate extent of environmental emission reductions	Evaluate the cumulative impact of implemented strategy on the environment, economics and social dimensions.
12-Adjust and modify solution	The purpose of this step is to make adjustments or modifications to the implemented solutions based upon the evaluation conducted in last Step (stepl 1)	Modify/change as needed technology, cost, implementation mode.	Modify/change as needed technology, cost, implementation mode, criteria, performance indicators.

with regards to environmental, economic, and social criteria agreed upon by the team.
- Including ELECTRE III model requirements in all stages of decision-making and steps involved with solution formulation. For example, in design of operation audit and diagnosis, data collection, data management, pollution source identification, waste characterization, and development, ranking and prioritization of waste management strategies according to their sustainability scores.

Implementation of the SEMS framework is a proactive approach to mitigating potential economic, social, and financial risks associated with the implementation of waste management projects. Use of the SEMS enables an organization to ensure sustainability while undertaking pollution prevention, clean production, pollution control projects or technological innovations that can reduce its environmental impact. The proposed framework would assist organizations that are not sure how to start on the path towards sustainability as well as those that are already implementing advanced programs in pursuit of sustainability.

Since the SEMS framework is rooted in the core requirements of the selected multi-criteria decision analysis ELECTRE III method, an overview of the most commonly used multi-criteria decision analysis methods and their applications is provided. Built on those premises, steps involved with the design and implementation of the SEMS framework are described in Sections 3.2 and 4 (case study).

3. Multi-criteria decision analysis methods

3.1. Overview

Multi-criteria decision analysis (MCDA) tools can be customized to incorporate value judgments of individual decision makers or multiple stakeholders. Most decision analysis methodologies share similar steps of organizing data into a decision matrix, but they differ in synthesizing matrix information and ranking of the alternatives. MCDA tools utilize various optimization algorithms to rank options, selecting a single optimal alternative or differentiating between acceptable and unacceptable alternatives.

Decision support tools such as PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations), ELECTRE (Elimination Et Choix Traduisant la Realité), AHP (Analytical Hierarchy Process), MAUT (Multiattribute Utility Theory), SMART (Simple Multi-Attribute Rating Technique), and different forms of linear programming (LP) have been studied in a wide range of applications (Kiker et al., 2005).

MCDA methods, more specifically, utilize a decision matrix of criteria and performance scores to provide a systematic analytical approach to integrating risk levels, uncertainty, and valuation, which enables evaluation and ranking of many alternatives (e.g. projects to be undertaken). While data organization steps are shared by most methodologies, each methodology synthesizes information differently. Multi-attribute utility theory (MAUT), multi-attribute value theory (MAVT), and the analytical hierarchy process (AHP) are more complex methods that use optimization algorithms, whereas outranking methods use a dominance approach. MAUT is a "compensatory" method aimed at identifying the net benefits of a decision. Similar to MAUT, AHP aggregates various facets of the decision problem using a single optimization function known as the objective function. Table 2 summarizes elements of the decision process in an MCDA (Linkov and Ramadan, 2004).

The method proposed for design of the sustainable environmental management system (SEMS) framework is ELECTRE III, which draws together the strengths of most MCDA models. This method has

Table 2
Decision process in MCDA (inspired by Linkov et al., 2006).

Element of decision process	Multi-criteria decision analysis
Define problems	Stakeholder input incorporated at beginning of problem formulation stage. Often provides higher stakeholder agreement on problem definition. Thus, proposed solutions have a better chance at satisfying all stakeholders.
Generate alternatives	Alternatives are generated through involvement of all stakeholders including experts. Involvement of all stakeholders increases likelihood of novel alternative generation.
Formulate criteria by which to judge alternatives	Criteria and sub-criteria hierarchies are developed based on expert and stakeholder judgment.
Gather value judgments on relative importance of criteria	Quantitative criteria weights are obtained from decision-makers and stakeholders.
Rank/select final alternatives	Alternative chosen by systematic, well defined algorithms using criteria scores and weights.

been also used successfully in analysis of many engineering and environmental policy projects (Salminen et al., 1998; Hokkanen and Salminen, 1997; Karagiannidis and Moussiopoulos, 1997). An overview of the ELECTRE III approach is provided to illustrate how decision problems can be formulated, and project ranking could be carried out upon formulation of the decision objectives, project alternatives and their associated criteria, thresholds, and weights.

3.2. ELECTRE III decision analysis method

Good decisions typically require a very good decision process and consideration of the decision problem's particular conditions and factors, as well as demographics and characteristics of the decision-makers involved (experience, background, personal relationships, etc.). These variables can have a significant impact on the outcome and results of the decision-making process. The ELECTRE III method allows for the consideration of such variations, merging both quantitative and qualitative data without requiring conversion to a single scale (Ulubeyli and Kazaz, 2009; Shanian et al., 2008). The ELECTRE III method operates on the assumption that where possible, the subjective and objective components of the decision process should be separated.

A decision problem can be conceived as comprising a set of objectively defined alternatives and a set of subjectively defined criteria. The relationship between the alternatives and the criteria is described using attributes that describe, as objectively as possible, the features of alternatives that are relevant to the decision problem. Each criterion attempts to reflect a decision-maker's preference with respect to certain features of the decision problem. These preferences, specific to a decision-maker, are inherently subjective. The criteria are formed utilizing attributes in a subjective manner.

Fig. 2 illustrates the alternative-attribute-criteria mappings along with the subjective-objective separation (Buchanan et al., 1999). The objective data (which does not include decision-maker preference) is captured in the performance matrix. The subjective preference data is gathered from the decision-makers in the form of thresholds (p, q, v) and weights (w) (Roberts and Goodwin, 2002).

The goal of structuring the decision problem into objective and subjective components places a clear boundary around the preferences of the decision-maker(s). It also allows the evaluation of alternatives (in terms of attributes) to be undertaken as objectively as possible. Each project or alternative can be defined by its attributes, which are then related to the criteria. For example the

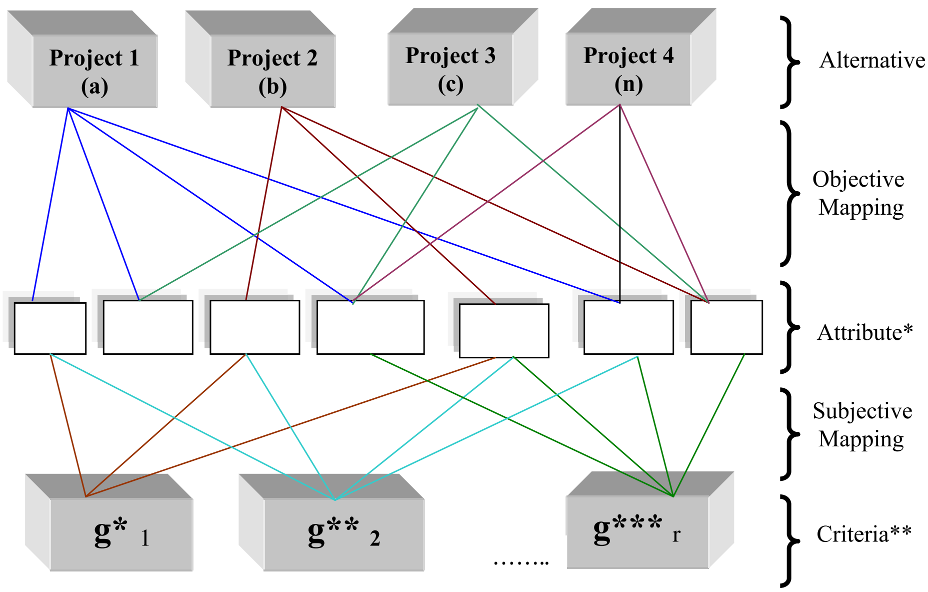

Fig. 2. Alternatives, attributes, and criteria mapping in ELECTREE III (inspired by Buchanan et al., 1999): * economic sustainability, **environmental sustainability, ***social sustainability.

criteria (and associated attributes in brackets) for sustainable projects could be formulated as Economic (net present values tax, depreciation, salvage values, different financing models), Environmental (negative externalities due to pollution, ecological and human health damage), and Social (stakeholder values at internal and external systems). Assessing each project across each criterion with the help of experts (including internal and external DMs) who are familiar with the project detail produces a matrix of impacts or performance.

3.3. ELECTRE III modeling approach

3.3.1. Defining relative importance and thresholds

The outranking model constructed by assuming defined criteria, gj, $j = 1, 2, \ldots, r$ and a set of alternatives A as $(a, b) \in A$. Under these assumptions the preference modeling assumes that $a\mathbf{P}b$ (a is preferred to b) $g(a) > g(b)$, and/or $a\mathbf{I}b$ (a is indifferent to b) so $g(a) = g(b)$. In contrast, ELECTRE methods introduce the concept of an indifference threshold, q, and the preference relations are redefined as $a\mathbf{P}b$ (a is preferred to b) $g(a) > g(b) + q$, and $a\mathbf{I}b$ (a is indifferent to b) $|g(a) - g(b)| \le q$. When approaching the solution, there could be a point at which a decision maker changes from being "indifference" to being strict "preference" when evaluating alternatives based on the performance and criteria. At this stage, model must introduce a buffer zone between indifference and strict preference; i.e. a zone of "weak preference" that is also a binary relation like **P** and **I** above. Now we have a double threshold model (relations **P**, **I**) with an additional binary relation **Q**, which measures weak preference as follows:

$a\mathbf{P}b$ (a is strongly preferred to b) $g(a) - g(b) > p$.
$a\mathbf{Q}b$ (a is weakly preferred to b) $q < g(a) - g(b) \le p$.
$a\mathbf{I}b$ (a is indifferent to b; and b to a) $|g(a) - g(b)| \le q$.

The choice of thresholds intimately affects whether a particular binary relation holds. A non- zero value is recommended for the choice of thresholds.

The ELECTRE III outranking model now requires values for three criterion thresholds, the indifference threshold ($\boldsymbol{q}$), the preference threshold ($\boldsymbol{p}$) and the veto threshold ($\boldsymbol{\nu}$). Rogers and Bruen (1998) propose a method for applying the standard ELECTRE III model to decision-aid problems within the formal mechanism of environmental impact assessment that involves a new, more comprehensive approach for specifying realistic limits for $\boldsymbol{p}$, $\boldsymbol{q}$ and $\boldsymbol{\nu}$ as $q < p < \nu$ (Rogers and Bruen, 1998).

Using thresholds, the ELECTRE method seeks to build an outranking relation **S** where $a\mathbf{S}b$ means that "a is at least as good as b" OR "a is not worse than b." Each pair of alternatives a and b is then tested in order to check if the assertion $a\mathbf{S}b$ is valid or not.

3.3.2. Concordance and discordance principles

The *concordance* principle requires that a majority of criteria, after considering their relative importance, is in favor of the assertion (the majority principle), while a *non-discordance* principle requires that within the minority of criteria that do not support the assertion, none of them is strongly against the assertion (the respect of minorities principle). The operational implementation of these two principles assumes that all criteria are to be maximized. The *outranking relation* for each of the "r" criteria can be then defined as " $a\mathbf{S}jb$ "that means "a is at least as good as b with respect to the jth criterion, when $j = 1, \ldots, r$. At this stage we can claim that the jth criterion is in "concordance" with the assertion $a\mathbf{S}b$ if and only if $a\mathbf{S}jb$ or if $gj(a) \ge gj(b) - qj$) (even if $gj(a)$ is less than $gj(b)$ by an amount up to qj, it does not contravene the assertion $aSjb$ and therefore is in concordance (harmony)). Consequently, the jth criterion is in "discordance" with the assertion $a\mathbf{S}b$ if and only if $b\mathbf{P}ja$ or if $gj(b) \ge gj(a) + pj$ (if b is strictly preferred to a for criterion j, then it is clearly not in concordance with the assertion that $a\mathbf{S}b$ (disharmony)). This steps are repeated for each criterion j, and for every pair of alternatives $(a,b) \in A$, as we need to identify if there is harmony or disharmony with the assertion "$a\mathbf{S}b$"; that is, "a is at least as good as b".

3.3.3. Measuring strength of assertions

Using the concordance and discordance concepts, the strength of the assertion aSb can be evaluated by developing a measure of concordance, as contained in the concordance matrix $\mathbf{C}(a,b)$, for every pair of alternatives $(a,b) \in A$. Assuming kj to be the importance coefficient (or weight) for criterion j outranking relation can be estimated as follows:

$$C(a,b) = \frac{1}{k}\sum_{j=1}^{r} k_j C_j(a,b), \quad \text{where } k = \sum_{j=1}^{r} k_j$$

where:

$$C_j(a,b) = \begin{cases} 1, & \text{if } g_j(a) + q_j \geq g_j(b) \\ 0, & \text{if } g_j(a) + p_j \leq g_j(b), \quad j = 1, \ldots r \\ \dfrac{p_j + g_j(a) - g_j(b)}{p_j - q_j}, & \text{otherwise} \end{cases}$$

Using data from performance table, we can now calculate the concordance index for the pair of projects (i.e. *a* and *b*). To calculate discordance, a further threshold called the veto threshold needs to be defined. The veto threshold, *vj*, allows for the possibility of ***a*S*b*** to be refused totally if, for any one criterion *j*, we have $gj(b) > gj(a) + vj$. The discordance index for each criterion *j*, *dj*(*a*,*b*) is calculated as follows:

$$d_j(a,b) = \begin{cases} 0, & \text{if } g_j(a) + p_j \geq g_j(b) \\ 1, & \text{if } g_j(a) + v_j \leq g_j(b), \quad j = 1, \ldots r \\ \dfrac{g_j(b) - g_j(a) - p_j}{v_j - p_j}, & \text{otherwise} \end{cases}$$

3.3.4. Developing credibility matrix S(a,b) from C(a,b) and dj(a,b)

From estimated concordance and discordance measures for each pair of alternatives/projects (*a*,*b*) ∊ *A* we can produce a measure of the degree of outranking; that is, a credibility matrix which assesses the strength of the assertion that "*a* is at least as good as *b*." The credibility degree for each pair (*a*,*b*) in *A* is estimated from:

$$S(a,b) = \begin{cases} C(a,b), & \text{if } d_j(a,b) \leq C(a,b)\forall_j \\ C(a,b)\cdot \displaystyle\prod_{j\in J(a,b)} \frac{1-d_j(a,b)}{1-C(a,b)} & \text{where } J(a,b) \text{ is the set of criteria such that } d_j(a,b) > C(a,b) \end{cases}$$

Where S(*a*,*b*) represents the degree of outranking and is equal to the C(*a*,*b*) or a product of

$$\frac{1-d_j(a,b)}{1-C_j(a,b)} \times C(a,b)$$

This formula assumes that if the strength of the concordance exceeds that of the discordance, then the concordance value should not be modified. If assertion that ***a*S*b*** is questioned, we need to modify **C**(*a*,*b*) according to the above equation (note, if the discordance is 1.00 for any (*a*,*b*) ∊ *A* and any criterion *j*, then we have no confidence that ***a*S*b***; therefore, S(*a*,*b*) = 0.00.

3.4. Ranking alternatives by distillation

The next step in the ELECTRE III method is to exploit the model and produce a ranking of projects from the credibility matrix upon construction of two preorders using a descending (selecting initially the best-performing alternatives, and finishing with the worst), and ascending (selecting first the worst rated alternatives and finishing with the best) distillation (see Fig. 2). This step requires determination of a "credibility value" such that only values of S(*a*,*b*) that are sufficiently close to it are considered (λ = maximum value of S(*a*,*b*) and s(λ) = discrimination threshold). The next step of distillation is to create a "T" matrix which takes values of 1 if S(*a*,*b*) > λ-s(λ) and 0 otherwise for each *a*,*b* ∊ *A* assuming cutting level of outranking to be λ-s(λ) (Tam et al., 2003). The qualification of each project is estimated from Δ (row values total- column total) in the matrix T.

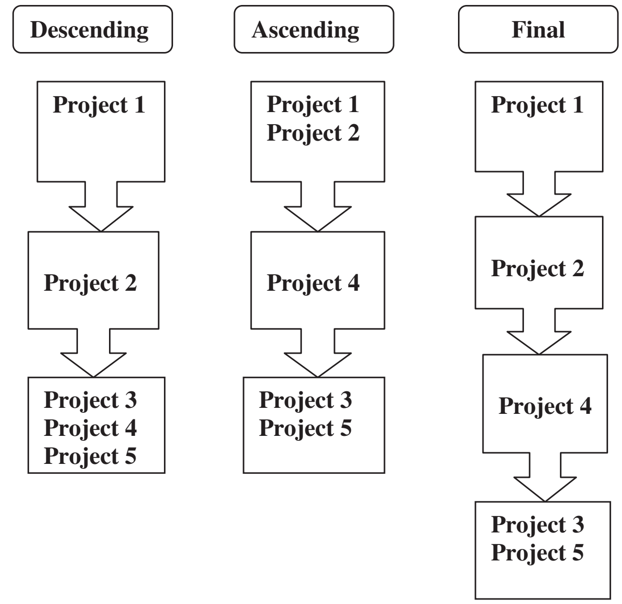

Fig. 3. Example ranking for five alternatives (a hypothetical example).

Fig. 3 presents an example outranking outcome. As shown, Project 1 is preferred to Project 2 and Project 4, while Project 3 and Project 5 are ranked together.

The last step in the ELECTRE III technique is the sensitivity or robustness analysis. A sensitivity analysis of the final rankings to changes in the thresholds and weights should be undertaken so as to appreciate the robustness of the ranking procedure. (Buchanan et al., 1999; Marzouk, 2011).

4. Application of Multi-criteria decision analysis methods: SEMS design

4.1. Background

The urgency of attending to the environmental issues and finding the most practical and sustainable solution to address them is well acknowledged, and has been more aggressively pursued in recent years. Examples include examining application of different Multi-criteria Decision Analysis (MCDA) methods with capability to take into account a variety of criteria apart from cost to assist with selecting the most relevant technical solutions for managing waste

(Mendoza and Prabhu, 2003a, 2003b; Hokkanen and Salminen, 1997; Roussat et al., 2009).

Regardless of the type of project, the other main objective of using MCDA is to assist with proper data collection, design, characterization, scoring, ranking, and prioritization of potential solutions to a specified problem according to a pre-established set of criteria and their respective weights (Hermann et al., 2007; Mendoza, and Prabhu, 2003b).

Without any standardized procedure, application of MCDA methods has been randomly introduced to environmental disciplines. For example, this method was used for the assessment of stakeholder involvement when pursuing management of contaminated lands (Linkov and Ramadan, 2004), policy development, manufacturing and services, medical, military and climate change studies, industrial facility sitting, and even risk analysis (Pohekar and Ramachandran, 2004; Kiker at al., 2005; Linkov et al., 2007). Potential applications of multiple-criteria methods – mainly ELECTRE III – have been recently suggested for assessing technical and design dimensions of selected environmental policy projects (Hokkanen and Salminen, 1997; Salminen et al., 1998; Tam et al., 2003; Kiker et al., 2005; Roussat et al., 2009; Marzouk, 2011).

Salminen et al. (1998), analyzed and compared three multi-criteria decision methods (SMART, PROMETHEE, and ELECTRE III) in the context of assessing environmental problems. Their result suggested that the main technical difference between these methods is in how information for the criteria is selected and synthesized.

In this study we selected the ELECTRE III method for inclusion in the development of the SEMS framework due to:

- Its flexibility,
- Prospects for conducting pair-wise comparisons between different options (outranking relations),
- The level of sophistication and involvement in outranking relations,
- Capability to select the (single) best solution,
- Ability to work with a minimal set of the most preferred actions,
- Subjective functions for defining categories such as relative importance of each criterion and veto option,
- Capability to work with any type of scale,
- Ability to produce predictions that reflect the "criteria" weights independently of the scales,
- Its recognition and reported practical applications (Virtual Mobility in Decision Science http://www.vrtuosi.com)

The design of Sustainable Environmental Management Systems (SEMS) is discussed in more detail in the following section. As indicated, SEMS is designed in response to the urgency and the growing need for developing a universal framework that is highly adaptable to different industrial settings, and addresses the complexity of the environmental problems and characteristics of socioeconomic systems. The proposed SEMS, therefore, is a common sense tool for planning, analyzing, scoring, and selecting sustainable, yet realistic solutions to address environmental problems and/or appropriate sustainability initiatives.

4.2. Design of sustainable environmental management systems (SEMS) framework

The proposed stepwise methodology for designing multi objective SEMS is built upon, and complements, the existing EMS framework and ISO 14000-14001 guidelines. This system, however, has the capability of the multi-criteria decision analysis model ELECTRE III, and as such can be used to select the best environmental management strategies according to their cumulative impact scores on the environment, economy, and social systems.

Both the EMS and ELECTRE III are accepted approaches and proven to be effective decision-making tools. While an EMS serves as a set of processes and practices that enable an organization to reduce its emissions and environmental impacts, and supports implementation of CP/P2 projects, the SEMS is designed to assist in selecting the most realistic, integrated and sustainable solution to waste problems. The SEMS framework also involves a continuous cycle of planning, implementing, reviewing and improving the processes and actions that an organization should undertake in order to meet its business, social, and environmental goals in a sustainable manner.

The proposed step-by-step framework for design of the SEMS uses sustainable development criteria relevant to operational initiatives and design and characterization of waste management programs. Per se, it encourages the use of different types of sustainable development indicators or assessment procedures to assist with selecting performance criteria. Example criteria and indicators include but are not limited to those proposed in Tisdell (1996); Mendoza and Prabhu, 2003a, 2003b; Labuschagne and Brent, 2007; Comoglio and Botta 2012).

The SEMS provides structure, formalizes the process and lays out detailed steps and procedures to follow, and as such is especially helpful for organizations that are making an initial move towards sustainability. The step-by-step roadmap for the design of the SEMS framework is presented in Fig. 4 and explained and compared to those of the EMS (ISO 14000-based EMS design) in Table 2a and b. As shown, the main objective of using ELECTREIII in SEMS is to assist with proper data collection, process audit, design of appropriate criteria and formulation of solutions that are industry/local specific, followed by characterization, scoring, ranking, and prioritization of potential solutions according to pre-assigned (established) set of criteria, performance indicators, thresholds and weights.

The main differences between the traditional EMS and the proposed SEMS frameworks are in the steps involved with setting goals and designing the policy for addressing environmental problems and issues; configuring the SEMS team and defining their tasks and responsibilities; developing the structure and requirements for audit and data collection according to a set of performance criteria developed by the SEMS team, and selecting data analysis methods and models; planning for customized environmental management strategies including alternative solutions according to industry's culture, business model, and developmental goals and internal and external stakeholders values; characterizing and ranking potential management strategies and their alternatives using the ELECTRE III method and selecting the best option according to a set of pre-defined weighted criteria.

The proposed SEMS framework is in line with the Rio+20 sustainable development goals, objectives and guidelines that call for action and results-oriented strategies and institutional frameworks that could provide inter-linkages among the multiple stakeholder's key issues and challenges at all relevant levels, yet is capable of providing solutions according to the three dimensions of sustainable development. (United Nations General Assembly Agenda Item 19 Sustainable Development: http://www.unepfi.org/events/2012/unepfirio20/index.html).

5. Case study: design of SEMS framework for GamaPro industry: spent yeast sustainable waste management

5.1. Project overview

This example case study demonstrates how an SEMS can be designed and used to select the most relevant and sustainable waste

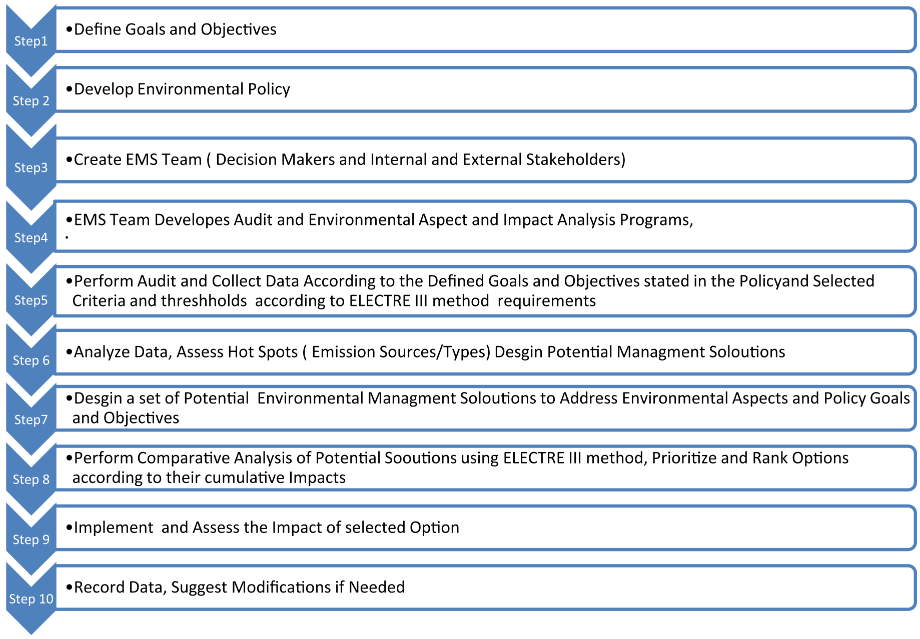

Fig. 4. Steps involved with SEMS design.

management solution to a selected waste stream at GamaPro industry.

GamaPro is a hypothetical manufacturer modeled after an actual well-managed, sustainable manufacturer of energy drinks and diet bars. Although this company is in a full compliance with environmental regulations, its environmental manager is planning to assess and identify the most proactive and sustainable methodology for addressing their spent yeast waste stream which is not currently regulated (a voluntary, proactive approach). Upon careful consideration of their options, the company decided to adopt the SEMS framework in order to manage not only the current yeast waste stream in the most sustainable manner, but also to identify other areas of improvement which may present themselves in the near future.

5.2. Development of the SEMS framework

5.2.1. SEMS team formation and training

The first step upon obtaining upper management commitment and formulating a draft environmental and sustainability policy was to establish the GamaPro SEMS Team that consisted of top management representatives (to convey management views and company's culture); internal and external stakeholders (to address employee, community, and regulatory interests); accounting and purchasing departments (to address financial constraints and supplier/customer interests); product design and manufacturing representatives (to account for material costs/waste characteristics, technological barriers/constraints, energy and efficiency issues, and point out potential areas of process improvement and implementation of the pollution prevention and cleaner production options); and one or several representatives from the marketing and public relations departments.

The team was briefed about the current waste issue and the company's desire to find a sustainable solution for managing it. The SEMS team was also asked to review and comment on the company's developmental goals, environmental and sustainability policy and stated goals and objectives. They were also familiarized with the manufacturing process, operations, and the waste streams the industry currently manages.

5.2.2. Process audit and data collection

An overview of the steps involved with selecting project performance criteria and associated thresholds and weights (*i.e. on evaluating each solution economic, environmental, and social impacts*) based on which management could compare and rank potential waste management solutions was provided and explained to the team in detail while providing example applications. The SEMS team was also informed about the decision-making model specifications and capabilities to select the most sustainable option for managing the waste stream of concern.

A process audit and data collection strategy was then formulated according to the organizational and operational boundaries. The audit included walkthroughs, interviews, review of the environmental and operating permits, and other relevant data such as OSHA reports and requirements, and the current state of the company's environmental compliance. Through document review and site visits it was possible to collect sufficient data for the analysis of processes and characterization of the spent yeast waste stream.

5.2.3. Performance criteria

The selected criteria and associated indicators in this study consisted of the following:

1 Economic Criteria: Cost to the company (U.S. $)
2 Environmental Criteria: Mass of waste diverted from off site disposal (lb/year)
3 Social Criteria: Potentials for job creation (number of jobs or increased pay in $)

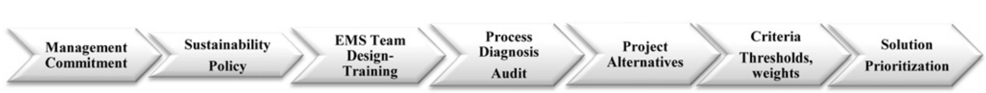

Fig. 5. Steps involved with design and use of SEMS in GamaPro case study.

5.2.4. Selection of waste management options

The SEMS team reviewed a list of alternative waste management options that was prepared by the engineering division prior to selecting the most sensible and practical ones for further analysis and ranking according to their impact scores. The pre-screened options were mostly “hardware”, i.e., operation/technology based. The “software” options such as management- regulatory- based solutions were not included in the list of options presented to the SEMS team.

The list consisted of projects such as managing waste via composting, using waste in development of biosorption, using waste as additive in animal feed manufacturing, treating waste by anaerobic digestion, and/or using this waste in a process involved with producing genetically engineered algae. The top three waste management options selected in this study were involved with:

- Using waste in the development of a novel biosorption catalyst for removal of heavy metals from other industrial waste streams (Project 1),
- Composting waste (Project 2), and
- Using waste as an additive in manufacturing animal feed (Project 3).

These three options were then were ranked and prioritized using the ELECTRE III decision-making method and estimated values for each criterion (from auditing phase), and their subjectively defined thresholds and weights. Special care was taken to quantify criteria, thresholds, weights and their expected impacts in both the short and long term. This was a necessary approach due to expected volatility in the price of materials and labor, and the need for more reduction in the emissions in anticipation of future legislation and other factors.

When identifying suitable indicators to measure impacts of the projects on economic, social, and environmental systems we carefully evaluated the quality and the quantity of information that was available to us at the point of assessment as well as methodologies we could use to translate those. For example, sometimes it was desirable to translate all impacts into financial terms in order to make them easily understood by the team. On the other hand, it was difficult if not impossible to place an economic value on all environmental and social impacts we were evaluating. As such, in order to assist with the multi-dimensional characteristics of the impact assessment we also considered use of a sustainability cost accounting (SCA) procedure from literature whereby externalities of waste stream could be translated into financial terms (Labuschagne et al., 2005; Brent and Labuschagne, 2006).

The final decision on environmental criteria selection was to consider the mass of waste transformed in each option as an indicator of project impact on the environment. Fig. 5 presents steps involved with developing the SEMS framework and characterizing and ranking waste management options at GamaPro industry.

After examining many options, the values for each criterion were selected from relevant literature, or estimated from data collected during the audit and site visits. Preferences and thresholds represented the relative importance of the criteria to the SEMS team. Estimation of the orders and outranking included development of the concordance, discordance, and credibility matrixes (to assess the strength of assertion that for each pair (a,b) ∈ A) followed by descending and ascending distillation, estimation of the orders, and ranks for each selected project. The ranking process and modeling results are discussed in the following section.

Table 3a
Modeling steps involved with project ranking in GamaPro case study.

Performance matrix			
Criteria (q)[a]			
Projects/alternatives	Economics (C&OM) $1000	Environmental (Lb waste diverted)	Social (job creation)
P1	550	558	6
P2	650	120	4
P3	88	200	3
Thresholds[b]			
q	17	40	1
p	23	80	2
v	30	85	0
w	0.2	0.5	0.3
Concordance matrix			
	P1	P2	P3
P1	1	0.8	1
P2	0.2	1	0.5
P3	0	0.8	1
Discordance matrix			
	P1	P2	P3
P1	1	1	0
P2	1	1	0
P3	1	1	1

[a] Data are objective and reviewed/proposed by EMS team/decision makers.
[b] Thresholds could be assumed constant or estimated as a function of criteria: f(g(a)), (g(b), etc.).

Table 3b
ELECTRE III ranking results for GamaPro case study.

Credibility matrix: T Matrix[a]/decision table	P1	P2	P3	Total (row sum)
P1	1	0	1	2
P2	0	1	0	1
P3	0	0	1	1
Total (column sum)	1	1	2	
Qualification of alternative projects				
Rank	1	0	−1	

[a] Discrimination threshold: $\lambda = 1$, s$\lambda = 0.3$ modify.

6. Results and discussions

6.1. Modeling results

A summary of the steps involved with the solution formulation, data collection, data analysis, modeling, characterization and ranking of selected waste management projects are provided in Table 3a and Table 3b below. As shown, selected performance criteria for all three alternative projects were estimated for the economic (cost related to capital, operation, management (O&M) and transportation); environmental (total mass of waste that could be managed annually by each alternative project), and social (potential for job creation or increase in income) impacts.

The subjective parameters included thresholds p, q, ν, w, and λ that were decided upon carefully by conducting a series of meetings with the SEMS team. Also shown in these tables is the first set of modeling outputs (concordance and discordance results for selected projects). Table 3b summarizes our final findings and suggests the estimated credibility values for each project as well as each project’s qualification and ranking. As shown, Project 1 was preferred over Projects 2 and 3, respectively (please see Fig. 6). This was an expected outcome; although the process involved with converting this waste stream to catalysts requires initial resources, it is capable of handling a large volume of waste and requires a set

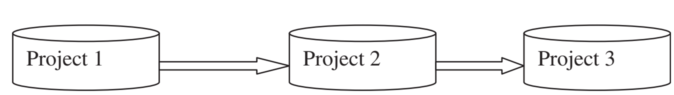

Fig. 6. Alternative project rankings for the GamaPro case study.

Table 4
Sensitivity analysis – changing thresholds.

	Range in which ranking remains Project 1 > Project 2 > Project 3 (maintaining $v > q > p$)	Range in which ranking becomes (P1 = P2 > P3) (maintaining $v > q > p$)	Range in which ranking becomes P1 > P2 = P3 (maintaining $v > q > p$)
Indifference (p)	0 to 437	438 to 460	–
Preference (q)	0 to 561	–	562 to 805
Veto (v)	0 to 116	–	for $v \geq 117$

Table 5
Sensitivity analysis and pair-wise weight changes.

Range of w for which ranking remains Project 1 > Project 2 > Project 3 ($w \geq 0$, sum of $w1,w2,w3 = 1$)			
Scenario 1-a	*Economic*	*Environmental*	*Social*
Economic	Varies	Varies	Fixed
Range of w for P1>P2>P3	0.001 to 0.699	0.7-w	0.3
Scenario 1-b	*Economic*	*Environmental*	*Social*
Environmental	Varies	Varies	Fixed
Range of w for P1>P2>P3	0.7-w	0.001 to 0.699	0.3
Scenario 2-a	*Economic*	*Environmental*	*Social*
Economic	Varies	Fixed	Varies
Range of w for P1>P2>P3	0.001 to 0.5	0.5	0.5-w
Scenario 2-b	*Economic*	*Environmental*	*Social*
Social	Varies	Fixed	Varies
Range of w for P1>P2>P3	0.5-w	0.5	0 to 0.499
Scenario 3-a	*Economic*	*Environmental*	*Social*
Environmental	Fixed	Varies	Varies
Range of w for P1>P2>P3	0.2	0.001 to 0.8	0.8-w
Scenario 3-b	*Economic*	*Environmental*	*Social*
Social	Fixed	Fixed	Varies
Range of w for P1>P2>P3	0.2	0.8-w	0 to 0.799

of new expertise that would result in either hiring opportunities, or training and increase in trainees' salary.

6.2. Sensitivity analysis

Sensitivity analysis was performed to examine variations in the modeling output as a function of selected thresholds and estimated values for the three selected criteria. This analysis focused on evaluating the type(s) and the patterns of variations in the modeling output with alteration in the assumed values for the thresholds. Modeling for project ranking was subsequently repeated as conditions and values assumed for the thresholds were changed. For example one mode of analysis assumed different ranges of values for the p, q and v, and converted values assumed for the social criteria from number of jobs created to additional salary earned (assuming average salary of $50k for each job and restating social values by the product of multiplying job number by $50k, and then dividing those by 1000) while all other thresholds remained at their basic assumed values, unless otherwise required by $v > p > q$ rules. We also performed a pairwise analysis to evaluate the potential impact of the change in the assumed weights.

The results of our analysis, including those presented in Tables 4 and 5 were consistent and encouraging as they indicated that the ranking procedure is robust under any assumed conditions and/or imposed variability on modeling parameters.

7. Conclusion

Sustainable operations require strategies and frameworks that can support organizational initiatives while satisfying multiple objectives such as maximizing financial performance and shareholder values while eliminating or minimizing potentially negative environmental externalities.

This paper proposes the design of a sustainable environmental management system (SEMS), a customized framework for facilitating inclusion of stakeholder values and multiple economic, environmental, and social criteria in the decision-making process involved with managing industrial and production environmental externalities. The SEMS framework is designed based on the familiar EMS platform, and the requirements of the ELECTRE III multi-criteria decision analysis method that is proven to be the most effective and structured among well-know multi-criteria decision models. The SEMS framework requires a visible and ongoing involvement of the organization's leadership as well as internal and external stakeholders in the development of environmental sustainability policies, setting performance criteria, and selecting the most sustainable approaches to managing the organization's environmental externalities. Example applications include assessment and selection of the most sustainable cleaner production or pollution prevention strategy according to a set of criteria defined by the organization's internal and external stakeholders (see GamaPro case study). Accordingly, as shown in this study, SEMS can be adopted, configured, customized and appropriated to any organization's structure, culture, value system, and sustainable developmental goals.

It is important to take into account that while approaching the design and implementation of systems such as SEMS, organizations may face a number of challenges: lack of priority for developing a systematic and involved environmental management strategy, lack of resources (human, material and/or financial capital), lack of incentives for the company and stakeholders to participate in such efforts, organizational resistance to change, lack of interest in investing in voluntary programs, and most crucially, lack in senior leadership's understanding of environmental issues, resulting in lack of top-down support. To overcome resistance to change, the SEMS framework requires participation, training, and involvement of representatives from all areas of an organization.

While having the knowledge and the metrics to facilitate decision making process is important, we found that the biggest challenge organizations may face is how to access resources and utilize effective benchmarking as an integral part of their efforts towards achieving and maintaining sustainable operations.

It is also important to highlight the role of the financial sector in supporting such initiatives, as it has the ability to promote the allocation of capital to organizations and businesses that are interested in pursuing a sustainable operations strategy. Government initiatives could facilitate adaptation of strategies such as SEMS by designing and enforcing policy frameworks that require integration of environmental strategies such as SEMS within the corporate reporting cycle on a 'report or explain' basis as well as promote the availability of funding via the financial sector.

References

Brent, A.C., Labuschagne, C., 2006. Social indicators for sustainable project and technology life cycle management in the process industry. Int. J. Life Cycle Assess. 11, 13–15.

Buchanan, J., Sheppard, P., Vanderpooten, V., 1999. Project Ranking Using ELECTRE III. www.mendeley.com/./ranking-projects-using-the-electre-method (accessed 9.11.12.).

Comoglio, C., Botta, S., 2012. The use of indicators and the role of environmental management systems for environmental performances improvement: a survey on ISO 14001 certified companies in the automotive sector. J. Clean. Prod. 20, 92–102.

Grutter, J.M., Egler, H.P., 2004. From cleaner production to sustainable industrial production modes. J. Clean. Prod. 12 (3), 249–256.
Hokkanen, J., Salminen, P., 1997. Choosing a solid waste management system using multi-criteria decision analysis. Euro. J. Oper. Res. 98 (1), 19–36.
Hermann, B.G., Kroeze, C., Jaw, W., 2007. Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators. J. Clean. Prod. 15 (18), 1787–1796.
Karagiannidis, A., Moussiopoulos, N., 1997. Application of ELECTRE III for the integrated management of municipal solid wastes in the Greater Athens area. Euro. J. Oper. Res. 97, 439–449.
Khalili, 2011. Practical Sustainability: From Grounded Theory to Emerging Strategies. Palgrave McMillan, NY. Ch 5.
Kjaerheim, G., 2005. Cleaner production and sustainability. J. Clean. Prod. 13, 329–339.
Kiker, G.A., Bridges, T.S., Varghese, A., Seager, T.P., Linkov, I., 2005. Application of multi-criteria decision analysis in environmental decision making. J. Integ. Env. Assess. Manag. 1 (2), 95–108.
Labuschagne, C., Brent, A.C., van Erck, R.P.G., 2005. Assessing the sustainability performances of industries. J. Clean. Prod. 13 (4), 373–385.
Labuschagne, C., Brent, A.C., 2007. Sustainability assessment criteria for projects and technologies: judgments of industry managers. S. Afr. J. Ind. Eng. 18 (1), 19–33.
Linkov, I., Satterstrom, F.K., Steevens, J., Ferguson, E., Pleus, R.C., 2007. Multi-criteria decision analysis and environmental risk assessment for nanomaterials. J. Nan. Part. Res. 9, 543–554.
Linkov, I., Satterstrom, F.K., Kiker, G., Batchelor, C., Bridges, T., Ferguson, E., 2006. From comparative risk assessment to multi-criteria decision analysis and adaptive management: recent developments and applications. Environ. Int. 32, 1072–1093.
Linkov, I., Ramadan, A.B., 2004. Multi-criteria Decision Analysis: A Framework for Structuring Remedial Decisions at Contaminated Sites. In: Comparative Risk Assessment and Environmental Decision Making. Kluwer Academic Publishers, Netherlands. 15–54.
Mendoza, G.A., Prabhu, R., 2003a. Qualitative multi-criteria approaches to assessing indicators of sustainable forest resource management. J. Forest. Eco. Manag. 174, 329–343.
Mendoza, G.A., Prabhu, R., 2003b. Multiple criteria decision making approaches to assessing forest sustainability using criteria and indicators: a case study. J. Forest. Eco. Manag. 13, 109.
Marzouk, M., 2011. M.M. ELECTRE III model for value engineering applications. J. Autm. Constr 20, 596–600.
Pohekar, S.D., Ramachandran, M., 2004. Application of multi-criteria decision making to sustainable energy planning: a review. J. Renew. Sustain. Energy Rev. 8, 365–438.
Roberts, R., Goodwin, P., 2002. Weight approximations in multi-attribute decision models. J. Multi-crit. Decis. Anal. 11, 291–303.
Rogers, M., Bruen, M., 1998. Choosing realistic values of indifference, preference and veto thresholds for use with environmental criteria within ELECTRE. Europ. J. Opera. Reas. 107, 542–551.
Roussat, N., Dujet, C., Méhu, J., 2009. Choosing a sustainable demolition waste management strategy using multicriteria decision analysis. J. Waste. Manag. 29, 12–20.
Salminen, P., Hokkanen, J., Lahdelma, R., 1998. Comparing multicriteria methods in the context of environmental Problems. Europ. J. Opera. Reas. 104, 485–496.
Shanian, A., Milani, A.S., Carson, C., Abeyaratne, R.C., 2008. A new application of ELECTRE III and revised Simos' procedure for group material selection under weighting uncertainty. J. Knowl. Based. Systs. 2, 709–720.
Tam, C.M., Tong, T.K.L., Lau, C.T., 2003. ELECTRE III in evaluating performance of construction plants: case study on concrete vibrators. J. Cons. Innov. 3, 45–61.
Tisdell, C., 1996. Economic indicators to assess the sustainability of conservation farming projects: an evaluation. J. Agric. Ecosyst. Environ. 57 (2–3), 117–131.
Ulubeyli, S., Kazaz, A., 2009. A multiple criteria decision making approach to the selection of concrete pumps. J. Civil Eng. Manag. 15 (4), 369–376.
UNEP, 2001. Promoting Financing of Cleaner Production Investments – Human Resource Development Initiatives. Ari Huhtala and Jan Jaap Bouma. UNEP, Paris.
UN General Assembly – Agenda item 19 Sustainable development. Draft resolution Submitted by the President of the General Assembly. http://www.unepfi.org/events/2012/unepfirio20/index.html (accessed on 09.01.12.).
Virtual Mobility in Decision Science. http://www.vrtuosi.com (accessed on 09.01.12.).