A Paradigm Shift: An Introduction to Structured Decision Making for Sustainable Waste Management and Remediation – 15649

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ABSTRACT

In the past decades addressing DOE's environmental issues has focused primarily on modeling fate and transport of contaminants and human health risk assessment. Most often these modeling activities are carried out in a conservative fashion, usually beyond even the conservatism that is built into the associated regulations and guidance. Decisions are aimed primarily at compliance with regulatory objectives, rather than optimization. This leads to unnecessarily costly remediation and under-utilization of the nation's relatively few radioactive waste disposal facilities.

Risk assessment decisions under CERCLA and RCRA might seem to perform better, but if anything this is because the focus is on shorter-term decision-making because long term fate and transport modeling is not considered necessary in most cases. However, some more complex contamination problems suffer from the same basic issues as radioactive waste disposal in terms of the need for complex fate and transport modeling and subsequent risk assessment. At least CERCLA addresses optimization in the feasibility study, but it does not address how to perform that optimization in the face of uncertainty or stakeholders who have different competing objectives.

Other environmental issues that fall outside the realm of DOE Orders, NRC regulations, and regulations such as CERCLA and RCRA, have found a different path towards effective decision-making. This includes land reuse and watershed management decisions, for which there is a focus on sustainability and on stakeholder involvement throughout the decision making process. EPA is using "structured decision analysis" to achieve the primary goal of maximizing societal welfare. These same tools and approaches can be brought into environmental and waste management decisions that need to be made by DOE. Structured decision analysis provides a formal process for capturing not only the science side of the problem, but also the costs and value judgments of the stakeholders, to reach an optimal solution. But this approach requires a paradigm shift within the DOE and NRC environmental and waste management programs. That is, it requires a willingness to engage a new approach that will provide a path towards effective optimization in the decision-making process for the complex environmental problems faced by DOE and NRC. Because of the current nature of problem solving for these types of problems, which involves many layers of conservatism, this structured decision analysis path towards optimization will also realize substantial cost savings for these programs, while maintaining or improving defensibility and transparency in the decision making process.

INTRODUCTION

The vast majority of remediation and waste management decisions are made without quantitative consideration of economic and socio-political factors. They are made instead based on quantitative metrics of human health risk. Sustainable decisions need to be made based on all three "pillars of sustainability" (economics, environment and social), and require understanding and characterization of the costs and values associated with each pillar. In addition, such decisions need to conform to regulatory or other legal requirements, which often constrains the decision space of interest. Although efforts are often made to include factors across all three pillars (for example, for decisions made under CERCLA), these efforts are usually qualitative, and hence difficult to defend. They lack technical defensibility, transparency and traceability. The purpose of Structured Decision Making (SDM) is to provide a quantitative framework whereby all aspects of a decision problem, such as remediation and waste management decisions, can be addressed quantitatively, and hence, defensibly, transparently and traceably.

Most decision-makers do not currently have access to useful or usable methods and approaches when are presented with choices that have significant impacts across all three pillars of sustainability. The goal of SDM is to provide that access by identifying or developing effective and user-friendly decision methods and approaches that empower decision-makers to explicitly and routinely incorporate all aspects of sustainability into their decision-making. To identify and develop these methods and approaches, implementation of SDM provides the tools needed for decision-makers and stakeholders to understand and characterize their knowledge of their current decision-making processes, and what methods and approaches they need to proactively and quantitatively address all aspects of sustainability in their decisions.

STRUCTURED DECISION MAKING

A decision-maker faced with a choice intuitively considers alternatives from which one is selected and the others are cut off. Resources are then allocated to the selected alternative. In an environment with multiple stakeholder perspectives and limited resources, it becomes necessary to clearly establish what to consider (criteria) for choosing among alternatives. Making decisions based on 'what is important' is the basis of value-focused decision-making and is fundamentally distinct from the more common alternative-focused decision-making. Keeney [1] describes the relationship between values and alternatives, as "Values are what we fundamentally care about in decision making Alternatives are simply means to obtain our values". Alternative-focused decision-making does include values, but often implicitly. They may not be clearly stated and thus not fully considered when making a decision.

Explicitly stating the values, and by extension the objectives and criteria used to define and measure their attainment, promotes a more transparent, inclusive, and defensible process and creates an environment for fostering options with better prospects for desired outcomes and minimal negative impacts [2]. For a decision-maker faced with a multi-faceted decision context involving several viewpoints across stakeholder groups, it is essential that the identification, creation, evaluation and selection of decision alternatives be grounded in the common values of the interested parties. Common values are those that most stakeholders will agree upon, values that they share even if at different levels. A decision process that incorporates Values-Focused Thinking will work toward finding those common values. Although adding an extra element before generating alternatives, Values-Focused Thinking yields several advantages that in the long run are worth the effort.

Applying the ideas of value-based decision-making to complex environmental management problems requires a conceptual framework or formalized process to ensure that a decision is consistent with stakeholder values, cognizant of tradeoffs among alternatives, and accounts for associated uncertainties and risks. Keeney [3] described the discipline of decision analysis (DA) as "a formalization of common sense for decisions that were too complex for the informal use of common sense."
SDM is a formal process that facilitates decision-making through the integration of science and fact-based information with stakeholder-derived values in an analytic-deliberative structure [2].
Our implementation of SDM provides a decision analysis framework for defensibly merging human dimensions, costs and value judgment, and technical input enabling decision-makers and stakeholders to:

(1) understand the underlying context of the decision;
(2) define desired outcomes and measurable objectives;
(3) identify options (actions) for achieving desired outcomes;
(4) evaluate options using applicable data and models; and
(5) take appropriate action when significant uncertainty exists.

These five steps form the core of a conceptual model for environmental and waste management decisions. They begin with a shared understanding of the problem and development of a set of objectives that it would be desirable to achieve. At that time, the possible actions that could be taken are identified. It is then possible to consider for each option (or combinations of options), how well they would help us achieve our desired objectives. The set of options that maximizes how fully we achieve our objectives is then identified as the optimal solution. From that point, various methods can be utilized to determine whether additional information might be valuable for increasing our confidence that we have identified the optimal decision, to determine which additional information would be most valuable, and to establish a plan for revisiting the decision in the future as conditions change, as appropriate.

Understand Context – Decision Landscape

The first step in SDM is to develop an understanding of the scope of the scientific and decision setting of the management problem, and to share this understanding amongst stakeholders.

The decision context may be characterized through development of a decision diagram, showing the political, regulatory, social, and institutional setting of the environmental management problem. This provides the critical context for the decision problem, including (for example): Are decision metrics specified by regulation or prior agreement? Are management options limited to a set of predefined alternatives, or is there flexibility to propose new approaches? Do the various stakeholders trust and utilize common sources for data and scientific assessment, or are there competing studies? Are mechanisms in place to include ecosystem services and externality costs in economic accounts for project evaluation?

When described together, the political, regulatory, sociocultural, institutional, environmental and scientific context provides the Decision Landscape. See Figure 1 for an example depiction of a decision landscape [4].

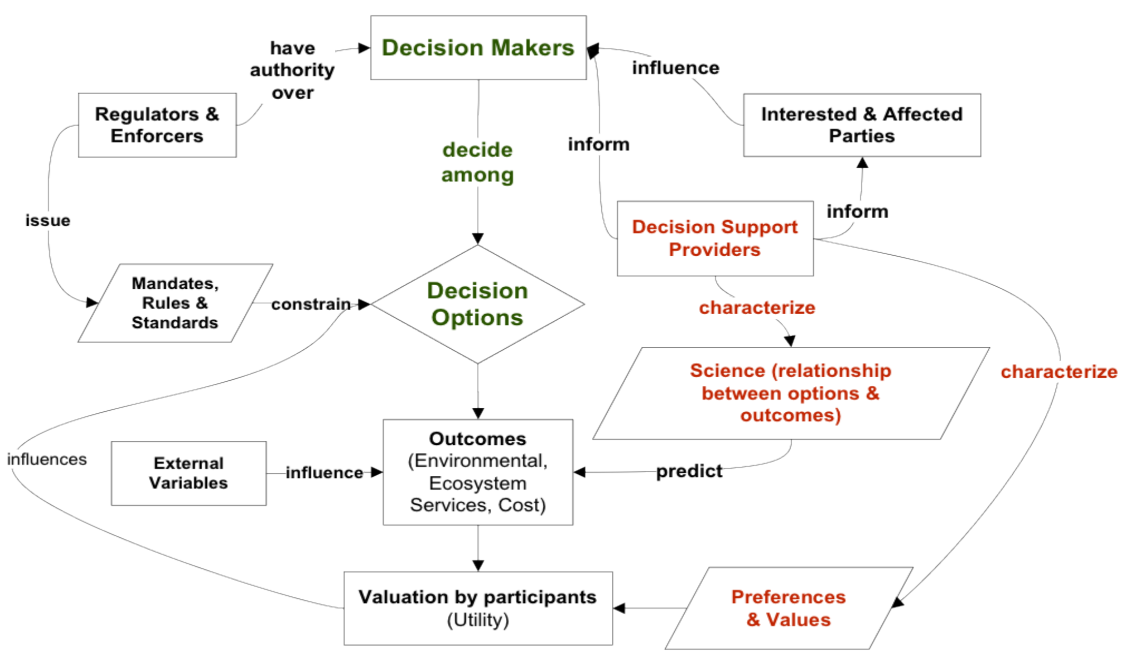

Figure 1: Example Decision Landscape Diagram

Social Network Analysis is a tool that can help to develop an understanding of how and with whom stakeholders, decision-makers, and the scientific community interact. There are many forms of social network analysis, and a variety of ways to depict them. A simple example diagram of a social network analysis is provided as Figure 2.

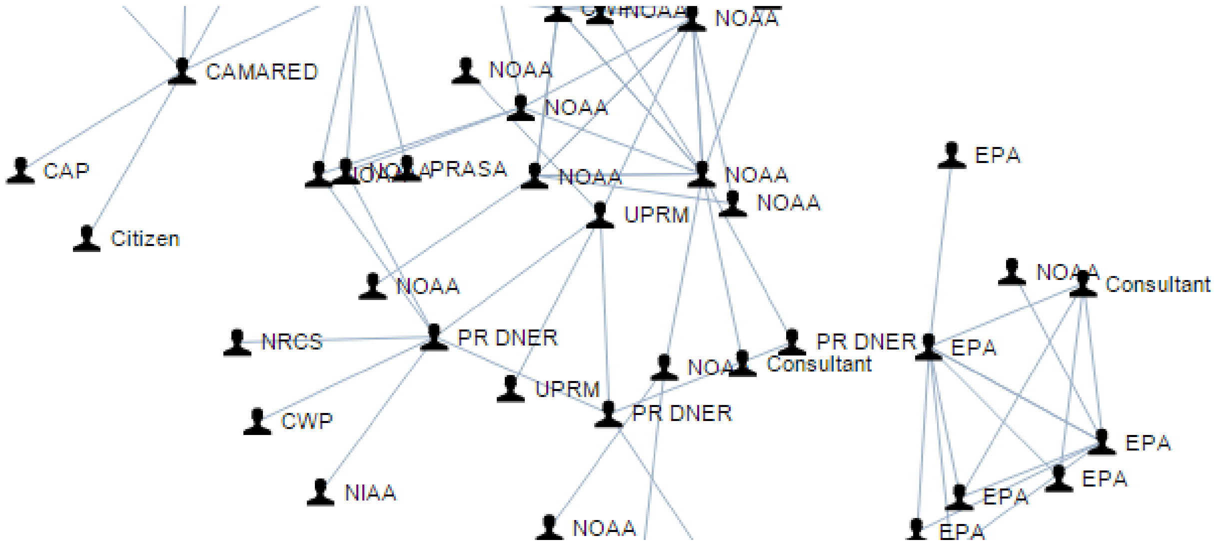

Figure 2: Example Social Network Analysis Diagram

Define Objectives

The second step is based on the Values-Focused Thinking approach to decision making [1]. "Values Focused Thinking" places decision making focus on stakeholder values rather than decision alternatives. Thus stakeholder values or objectives play a central role and guide all phases of the decision process, including development of decision alternatives and the collecting and analysis of the information needed to evaluate decision alternatives. This focus on objectives helps to ensure the decision processes produce solutions that are transparent in how stakeholder and decision makers needs and desires are satisfied.

During this step, stakeholder preferences and values are organized into an Objectives Hierarchy. An Objectives Hierarchy organizes the stakeholders' concerns into layers or a tree of objectives with broader objectives at the top (called Fundamental Objectives) with tiered sub-objectives that refine and provide more specifics or meaning on the Fundamental Objective. This process of thinking through and writing down objectives goes a long way towards determining:

- what information to seek
- explaining decisions to others, and
- helping to determine a decision's importance and, consequently, how much time and effort it deserves.

An objective has a specific definition under SDM, it specifies what you hope to achieve and is structured as a short phrase of a verb and an objective. Examples include:

- Minimize environmental damage
- Maximize profits

It is often important to clearly distinguish between Fundamental from Means Objectives. Means Objectives identify approaches for achieving a Fundamental Objective. For example, for the example Fundamental Objectives given above, associated Means Objectives might be to:

- Minimize loss of wetlands
- Minimize maintenance costs

The approach to developing an objectives hierarchy is somewhat of an art involving several steps:

1. Write down all the concerns that need to be addressed for the decision – collect together general thoughts and concerns
2. Convert these concerns into succinct objectives
3. Separate ends from means to establish fundamental objectives
4. Clarify what is meant by each objective
5. Query the stakeholders to determine if the objectives capture all relevant interests

When an objectives hierarchy is identified, each of the lowest level sub-objectives is associated with an attribute or measure by which the achievement of an objective can be measured. These Measurable Attributes are used to compare and evaluate decision alternatives under Step 4 – Evaluate Options. Thus, building the objectives hierarchy and defining measurable attributes is the cornerstone of defensible decisions.

Identify Options

Decision alternatives are explicitly derived from the decision context and objectives.
A good alternative has several characteristics [2], including that it is:

- complete and comparable
- value-focused
- fully specified
- internally coherent

Means Objectives are used as a path to development of Options. Means Objectives specify how the Fundamental Objectives can be achieved. Means Objectives then lead to specific Decision Options. Once a set of Options are identified, then Management Scenarios that are combinations of these Options can be established.   For example:

- Options:
    - Place site in/outside of wetlands
    - Establish institutional controls (the stronger these are, the lower the maintenance costs)
    - Depth of waste burial

- Management Scenarios:
    - In wetland, strong institutional controls, deep burial
    - In wetland, strong institutional controls, shallow burial
    - In wetland, weak institutional controls, deep burial
    - In wetland, weak institutional controls, shallow burial
    - Outside of wetland, strong institutional controls, deep burial
    - Outside of wetland, strong institutional controls, shallow burial

- Outside of wetland, weak institutional controls, deep burial
- Outside of wetland, weak institutional controls, shallow burial

Evaluate Options

The expected ability of these Management Scenarios to meet the stated objectives are then evaluated using environmental, economic, and social models. The starting point for building an environmental model is the conceptual model developed in Step 1 – Understand the Context. The model represents a compilation of the causal understanding of the system and mapping and monitoring information. Model choice, monitoring design, and mapping detail are all part of the decision process. The resources dedicated to each aspect of Evaluating Options should be considered in light of the Decision Context and the Objectives.

A key aspect of the comparison of Management Options is developing an understanding of our uncertainty on the impact of the changes in Measures. This requires a probabilistic approach to environmental modeling such that the uncertainty in various outcomes is understood. SDM provides a Bayesian modeling tool that could accommodate and integrate any environmental modeling approach into the decision analysis framework. This Bayesian approach provides a formal framework for merging knowledge and data, including these important advantages:

- Provides a rigorous framework for including modeling uncertainty in decisions; and,
- Promotes efficient allocation of resources: start with simple models, iteratively include more complex models as required by the decision with the level of model complexity driven by the value of information.

Take Action

The set of management options that best meet the defined objectives are implemented. The impact and effectiveness of these options is monitored and evaluated overtime under Adaptive Management to determine if the objectives continue to be met. If no set of management options fully meet the identified objectives, a Value of Information analysis can be undertaken to determine the most cost-effective course of action in developing an alternative set of management options for evaluation.
Adaptive management is often described as “learning by doing,” and its cyclical structure allows for improving management based on the outcomes of monitoring and evaluation of decisions and policies (Williams and Brown [5]). The adaptive management cycle begins with carefully identifying issues of concern, assessing baseline conditions, and planning for management decisions. After those decisions are implemented, the impacts of those decisions need to be carefully monitored throughout implementation.

The decisions and resulting impacts then need to be carefully evaluated to understand if they should be improved upon, changed, and whether or not the effort is successful enough to replicate in other areas. Any important adjustments identified in the evaluation should then be instituted. The cycle then continues on in feedback loops utilizing this new baseline as the assessment to plan for future projects or to refine existing efforts. These feedback loops are critical for fostering sustainability by allowing visitation of planning goals and through careful monitoring and evaluation to understand the efficacy of management decisions. The feedback loops also allow for incorporating and adapting to new information about a community, a policy or program, or scientific findings related to the decision.

Adaptive Management is an integral component of the structured decision making approach. In structured decision making, managers focus on clarifying the specific economic, environmental and social context of the decision being made, and use that understanding to define specific objectives and other evaluation criteria. These help to outline the critical components of the decision, prioritize and compare management options, and to evaluate the outcomes of decisions.

TECHNICAL DETAILS

For the interested reader, this section provides a bit of technical basis for the practice of decision analysis. Assume the set of attributes and value functions for each attribute are defined through elicitation or otherwise, where the value function for an attribute specifies a numeric score to each possible outcome for that attribute that represents the relative desirability of each outcome.

Attribute ranking is done in terms of swing weights, to help ensure that users are assigning ranks in terms of the potential *change* in value for the attribute, rather than just the value of the attribute itself. The user is presented with a hypothetical worst-case scenario – one that performs at the worst possible level for each attribute, and a best-case scenario – one that performs at the best possible level for each attribute. The user is then asked to pick one attribute for which they could move from the worst case to the best case, and that attribute is ranked highest. The process continues, choosing attributes to move from worst to best case, resulting in a complete ranking of the attributes.

Attribute ranks can then be converted to attribute weights via default methods, such as rank proportionality, or weights can be elicited conditional on the ranks. For example, the user can be presented with pairs of successively ranked attributes and asked to provide a relative importance to the higher-ranked attribute. If $r_{i+1,i}$ is the relative importance of the $(i+1)^{th}$-ranked attribute to the i^{th}-ranked attribute, then the n attribute ranks convert to importance weights as:

$$w_i = \frac{\prod_{j=1}^{i} r_{j,j-1}}{\sum_{k=1}^{n}(\prod_{j=1}^{k} r_{j,j-1})} \qquad \text{Eq. 1}$$

(where $r_{1,0} = 1$, for notational convenience).

Linear additive multi-attribute models are simple to employ and have been shown to work well in many different scenarios. Value functions for the individual attributes are normalized – shifted and scaled such that the values for each attribute range from 0 to 1, in order to match the way in which swing weights are constructed. Then the model takes the form:

$$Weighted\ Score_j = \sum_{i=1}^{n} w_i \times v_i(x_{i,j}) \qquad \text{Eq. 2}$$

where j is a particular risk topic, i is an attribute, w_i is an importance weight for attribute i, v_i is the normalized value function for risk topic j on attribute i, and $x_{i,j}$ is risk topic j's magnitude on attribute i. Ideally, the multi-attribute weighted scores for each management option are then examined by the user, allowing for feedback if the scores do not match intuition, and allowing for examination of the reasons that the scores deviate. Ultimately, the weighted scores are used as a basis for selection of the optimal solution.

CONCLUSIONS

Key components of structured decision analysis are the identification of objectives and management options that provide decision makers with multiple approaches for addressing an issue. Relevant stakeholders and decision makers can then weigh these different objectives and ascribe value to various possible levels of achieving each objective. In order to select an approach that best meets the objectives of the policy or program for the community, each management option (or set of management options) is evaluated against how well it would achieve the stated objectives. This prioritization of multiple alternatives according to agreed-upon objectives allows for a rational decision making process when dealing with complex decisions in uncertain environments.

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