A Paradigm Shift – The Key to Optimal, Defensible & Transparent Waste Management, Disposal & Remediation Decisions – 15236

Paul Black *, Paul Dixon **, Laurel Boucher ***, Tom Stockton *, Kelly Black *
* Neptune and Company, Inc., ** Los Alamos National Laboratory, *** The Laurel Co.

ABSTRACT

Current methods for structuring nuclear waste management, disposal, and remediation decisions are subject to three major limitations. First, they are based on a series of extraordinarily conservative assumptions. The dominant way of thinking is that, for example, conservative models yield better, safer decisions. Second, they lack methods to meaningfully address and incorporate the "human dimension". The dominant way of thinking is that the current approach is sufficient to bring together the values and interests of both internal and external stakeholders in making a decision. And third, they lack a formal method through which both internal and external stakeholders are encouraged collectively to "think through" complex problems that contain multiple competing objectives so that wise, socially acceptable, and scientifically-defensible decisions are made. To overcome these limitations, a paradigm shift is needed towards a holistic, integrated approach to structure nuclear waste management, disposal and remediation decisions. The first requirement of this paradigm shift is the realization and recognition that the problems faced are decision problems, and that there is a formal theory of decision analysis that can, and should, be used to support finding the best solutions. Decision analysis, very simply, is formalized common sense. The reason it is needed for complex problems is that there are too many moving parts (variables) for humans to manage with out the formalism. Decision analysis leads to addressing problem solving using a combination of a science-based model and a costs/values model. Expectation (“realism”) and uncertainty are addressed in the science-based models, whereas stakeholder values, preferences, and desires are addressed when modeling costs and value judgments. Science-based modeling tools have been developed, improved, and used since the current regulatory setting was introduced about 30 years ago. However, modeling of costs and value judgments has not often been addressed using any formal approach, despite the openings that exist in regulations (e.g., CERCLA’s modifying criteria and the concept of “as low as reasonably achievable” referenced in DOE Orders). A discussion of the need and rationale for this paradigm shift is presented, followed by a description of the technical basics of this approach to decision modeling, and ending with an explanation of the steps that are taken in this approach to structured decision-making. A software framework program called Guided Interactive Statistical Decision Tools (GiSdT – pronounced “gist”) is introduced that supports this paradigm shift.

INTRODUCTION

DOE environmental and waste management decisions have been made at sites in the DOE complex since the introduction of various regulations and guidance in the 1980s. These regulations established a process by which human health risks from exposure to residual radioactive contamination in the accessible environment could be evaluated. Implementation of the basic risk (or radiation dose) assessment process has advanced with the recent rapid improvement in computer technology. The evolution in approach to risk-based modeling has seen transition from simple deterministic screening decisions to probabilistic fate and transport and risk/dose assessment models. It has proved difficult, however, for regulations and guidance to keep up.

From the beginning of the regulatory era for environmental problems, the main focus has been problems that can be dealt with relatively easily. Conservative screening methods were developed for risk assessment, and this same simple approach was applied to regulatory compliance objectives. With few exceptions (e.g., 40 CFR 191), regulatory requirements were established to demonstrate compliance based on the notion that relatively simple deterministic screening risk assessments would be performed. Arguably this has sometimes proven sufficient, but the focus on deterministic conservative risk assessment modeling to support compliance has undoubtedly resulted in taking unnecessarily expensive actions. Some problems with this approach have become evident when CERCLA Records of Decision have needed to be amended, some radioactive wastes could not find a disposal option, and the licensing process for Yucca Mountain was suspended. These examples provide indications of problems with the current approach to environmental and waste management decision-making.

Exacerbating these problems are continual reductions in annual funding, spiraling costs of environmental clean up and radioactive waste management, the escalating challenges of complying with previously established and relatively inflexible agreements with state environmental agencies, and a desire (in some parties) to “finish the job” (complete DOE’s cleanup program and strategies for management of radioactive waste), while the most complex problems are still to be faced. If the approach is not changed, then success is likely to be unattainable. A paradigm shift is needed.

It is, perhaps, easy to cast these stones from afar, however it is important to recognize and acknowledge that the technology did not exist in the 1980s to implement the types of modeling and problem solving approaches that can be performed today, and that addressing environmental contamination was new back then. There is now an opportunity to learn from the past and implement better processes that take advantage of the lessons learned over the past 30 years or so, the vast improvements in computer technology, and innovative approaches that now exist for bringing costs and value judgments into solving science-based decisions.

Some improvements in methods and approaches have been made along with the advances in computer technology. For example, probabilistic modeling plays a greater role in modeling the fate and transport of contaminants, and also for risk/dose assessment. And, the increased speed or power of computers allows many more simulations to be run. However, these efforts have not gone far enough; probabilistic modeling is still often used in combination with deterministic modeling, conservatism has not been sufficiently removed in the transition from deterministic to probabilistic modeling, and compliance is still the primary goal. This is like adding new capabilities to a DOS-based computer system, instead of embracing a complete change in approach (a paradigm shift).

The consequences of the current system or approach are more far reaching than they might first appear. The current technical approach costs too much because it is mis-aimed, and results in conservative decisions that require unnecessary resources for subsequent actions that are taken. Where environmental management is concerned, continuing to apply the current approach will have even greater consequences as more challenging problems are addressed, and ever-reducing resources are being used unnecessarily. Where radioactive waste management is concerned, the implications are perhaps even greater. Poor decision-making for radioactive waste disposal not only results in greater costs, but also limits disposal capacity for each disposal site and for the disposal sites combined. Licensing disposal facilities is not straightforward, and an approach is needed that optimizes use of each existing disposal facility for specific waste streams, and use of all disposal facilities collectively. This type of optimization is not possible with current approaches to modeling that are conservative and compliance-based. And, additional computational power will not change the basic problem. Perhaps more importantly, poor decision-making at the radioactive waste disposal level impacts upstream decisions related to nuclear industries and nuclear policy, including energy and medical. Successful application of this paradigm shift would level the playing field for the nuclear industry, and avoid the current situation where “the radioactive waste management tail is wagging the nuclear industry dog”.

The purpose of this paradigm shift is absolutely not to avoid real environmental contamination problems for which DOE is responsible, either now or in the future. It is, specifically, to help focus resources on those real problems, and to make the best decisions possible given current knowledge and stakeholder values. Good decision-making is based on a balance of costs/values and the best understanding of the problem. Right now, there is an opportunity to effect a paradigm shift that brings new tools to the table to support more effective probabilistic modeling on the science-side of the decision equation, and introduce methods for evaluating costs and value judgments in stakeholder-driven structured decision making (SDM). This approach can be applied at several levels of decision making for waste management, including specific waste stream disposal decisions, optimal use of existing disposal facilities, and siting of new waste disposal facilities. For environmental management, the benefits include more effective resource management and cleanup. This approach could be used to manage environmental and waste management as an enterprise system. The paradigm shift is aimed at optimized decision-making rather than compliance-based decision-making, although compliance objectives can be used as a floor or threshold for optimization, so that the optimal decisions also ensure compliance. This innovative approach, which is currently being applied in some EPA, FDA and DoD programs, is critical for addressing the complex environmental and waste management problems that remain with the limited budgets that seem inevitable.

The advantages of such a paradigm shift are potentially huge. The paradigm shift means building decision models that include science-based models and models of costs and value judgments that represent what is (thought to be) known about a problem (and the associated uncertainties). This is far easier to explain to stakeholders than the more traditional conservative deterministic, or even probabilistic, models. It is difficult to explain conservative models that do not relate to actual site conditions; “realistic” models are far easier to explain because they are based on a genuine understanding of the problem. This paradigm shift is also needed to provide a more level playing field for nuclear industry, to make better use of limited resources, and to help future generations address these same problems.

This paper and associated panel session (WM2015 paper number 15236, and panel session 127) are part of a companion series of papers and presentations given at WM2015. The series includes WM2015 paper numbers 15650 ([1] structured decision making), 15650 ([2] guided interactive statistics and decision tools), 15087 ([3] stakeholder engagement), and 15651 ([4]) sensitivity analysis).

DESCRIPTION

Overview

DOE’s environmental and waste management decisions are driven on the science side by human health, and sometimes ecological, risk assessment. Decision making, however, requires more than simply considering the results of human health and ecological risk assessments. It also requires consideration of costs and value judgments. This is clear under CERCLA in the form of the “modifying criteria” (state acceptance, community acceptance). It is also possible under DOE Orders, using the concept of “as low as reasonably achievable” (ALARA). However, in traditional practice, if costs and value judgments are considered, the approach to doing so is often *ad hoc* and qualitative. The approaches are well intentioned, but are often informal and not quantitative. Coupling this with the current overly conservative approach to human health and ecological risk assessment, means that decisions are often difficult to defend in depth, and are often not transparent or traceable. This is particularly the case for complex problems to which simple screening level approaches are essentially applied.

Advances in technology have been applied to the science side of DOE environmental and waste management decision problems, such that complex computer programs have been developed and improved, and continue to be improved, to address fate and transport modeling and risk/dose assessment. Unaddressed is a formal approach for incorporating the costs and value judgments that are implicit in concepts such as ALARA (as low as reasonably achievable), and are required to complete a decision analysis. And yet, arguably, the greatest uncertainties in the decision making process are associated with the costs and values. It is curious that more technical effort is put towards fate and transport modeling, which is reasonably well developed, than in understanding the costs and stakeholder values associated with these complex decisions, for which models are not yet well developed.

That is not to say that costs and value judgments are not currently considered at all in the decision making process. However, they are not considered using formal quantitative methods. They are usually considered in an *ad hoc* fashion, which unfortunately inadequately addresses desirable attributes such as technical defensibility, transparency and traceability. The technology exists to continue to evolve risk-based decision making by acknowledging and incorporating formal decision analysis methods. This approach also provides an opportunity to change the way in which stakeholders are engaged in the decision-making process. Through use of decision analysis tools, stakeholders can be engaged in establishing the decision space, and participating in the subsequent identification of optimal solutions to environmental and waste management decisions.

Combining the two basic tenets of decision analysis (science-based modeling and costs/values modeling) allows for the formulation of better risk-based cost-benefit decisions in collaboration with the stakeholders. This process is not a short cut, but a thorough vetting of the issues, risks, and costs that go into determining best resolution of nuclear waste storage and cleanup decisions. The anticipated outcome of this process is a greater understanding and acceptance of the risks and associated costs that different levels of residual risk lead to in these decisions.

Decision analysis has existed as a science since the mid-1900s, but has not made it far into the environmental arena. Recent advances in approaches to implementation have better positioned decision analysis to successfully engage stakeholders in complex decision-making. The remainder of this paper provides an overview of these methods, described as stakeholder engaged structured decision-making, identifies the specific steps that are taken to implementation, and demonstrates application through an example for a fictitious radioactive waste disposal facility. The example is also used for demonstration in the panel session that is supported by this paper.

As noted above, the paradigm shift that is proposed here is based on applying more formal decision analysis approaches to DOE’s environmental and waste management problems. Applied decision analysis is, essentially, formalized common sense. This approach requires objectivity to optimize decision making, and effectively separates the science-based modeling from preferences and desires that are expressed through value judgments. This avoids the current situation in which preferences and desires are essentially built into science-based models through conservatism. Decision analysis manages science and values separately and properly. Decision analysis is about balancing preferences and desires with what’s likely to happen. This approach does not remove conservatism from decision-making, but places it squarely with value judgments where it belongs. Conservative decisions can still be made, but important decisions are no longer supported by unconstrained and arbitrary conservatism in science-based models. Instead, conservative decisions, if preferred, are made directly through specification of value judgments.

A decision analysis approach also places science-based modeling in the right context. Science-based modeling should be driven by the decision analysis needs. That way, the need for complex fate and transport modeling tools becomes clear when necessary in response to the requirements of the decision analysis. New computationally intensive or powerful tools, such as the Advanced Simulation Capability for Environmental Management (ASCEM [5]), might be useful, but the situations in which they are useful are defined or controlled through the decision analysis modeling, instead of building more complex models with no obvious need for doing so. Part of the decision analysis process involves uncertainty and sensitivity analysis, which can be used to identify where more effort needs to be put into model refinement or additional data/information collection.

The focus of this paper and associated panel session is on the costs and value judgments component of a stakeholder engaged structured decision analysis as it might be applied to DOE environmental and waste management problems. The focus is decision risk, and making decisions that balance stakeholder preferences and desires with the likelihood or probability of human health risk or dose. This paper and panel session follows the paradigm shift of focusing first on the decision risk, and using tools such as fate and transport models to support those decisions, as appropriate.

This approach to assessing decision risk is supported with a software framework program called Guided

Interactive Statistics and Decision Tools (GiSdT– pronounced “gist”). GiSdT is an open source, interactive, web-based program that is used to document stakeholder inputs during decision model development. GiSdT presents a relatively new approach to addressing the “human dimensions” of problem solving, and involves organizing stakeholder values and objectives prior to addressing decision options that might be available for optimization. That is, GiSdT addresses the costs and values side of a decision problem, and then interfaces with science-based models so that a proper decision analysis is performed that balances stakeholder concerns with the probability of human health risk or dose.

The paradigm shift is that of turning the focus …

- From a conservative to a “realistic” analysis
- From starting with the decision-science before the natural science (that is, from starting with the “Why?” before the “What?”)
- From an alternatives-focus to a values-focus

The paradigm shift results in solutions that …

- Are optimal, thus save DOE money
- Are safe and compliant
- Are defensible and transparent

Technical Approach

The technical approach that serves as the basis for the paradigm shift can be termed stakeholder engaged structured decision-making (SDM). SDM came to the fore in Gregory et al’s [6] book of the same name. Gregory et al took a value-focused approach to decision making, which can be differentiated from traditional approaches to decision analysis that focus first on decision options. Value-focused thinking was first described by Keeney [7], and was intended to make decision analysis more tractable, useful, and accessible to decision makers. The steps involved in this stakeholder engaged structured decision-making approach can be summarized as follows:

1. Understand context
    a. Regulatory, social, and environmental setting
    b. Scientific setting
    c. Decision landscape
    d. Conceptual model
    e. Social network analysis
2. Define objectives
    a. Fundamental objectives
    b. Measurable attributes
    c. Value functions
    d. Objectives preference weighting
3. Identify decision options
    a. Define options
    b. Tie options to objectives
    c. Develop management scenarios (combinations of options)
4. Evaluate decision options
    a. Develop science-based models (probabilistic modeling) for each option and measurable attribute
    b. Perform uncertainty analysis
    c. Perform sensitivity analysis
5. Take action
    a. Choose optimal decision option or collect more data/information (including model

refinement as necessary)

b. Iterate if necessary

GiSdT provides a software platform for capturing inputs provided for each of these steps, which allows the decision model to be fully transparent and traceable. Technical defensibility is obtained by completing the SDM process. GiSdT forces quantification at each step (e.g., value functions, weights, probability distributions), requiring stakeholder engagement for specification of value functions and weights. GiSdT implementation of SDM is essentially an implementation of Bayesian statistical decision analysis. This addresses multi-attribute utility and uncertainty characterized using probability distributions. This approach, using GiSdT technology, has been used by EPA on watershed management, brownfields revitalization, and coral reef management projects, and by other federal agencies such as FDA (food safety), DoD (unexploded ordnance risk), and NASA (climatology), as well as for some commercial applications. It is perhaps time to bring the same technology into DOE decision-making. This approach changes the focus of modeling from one of conservatism to optimization, which supports better decision-making. It engages stakeholders more effectively, so that value judgments and assumptions are addressed as inputs instead of as endpoints, and provides a structure to support decision-making that allows decisions to be defensible, transparent and traceable. The main steps are described in greater detail in each subsection that follows, including general discussion followed by specifics of the example used in the panel session mock demonstration.

Step 1: Understand context

The first step is to develop an understanding of the scope of the scientific and decision setting of the decision management problem. This is the only fully qualitative step of the SDM process as implemented in GiSdT and, consequently, includes flexibility in ways to describe the decision landscape. The decision context can be characterized using a decision diagram that shows the political, regulatory, social and institutional setting of environmental management problems. This provides context for the decision landscape. For example: Are decision metrics specified by law or prior agreement (regulation)? 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? The intent is to encourage broad thinking about the problem so that all perspectives are entertained. If there are many different stakeholder groups, then a social network analysis can also be useful for understanding the connections between the groups. An example decision landscape might look like Figure 1 [8].

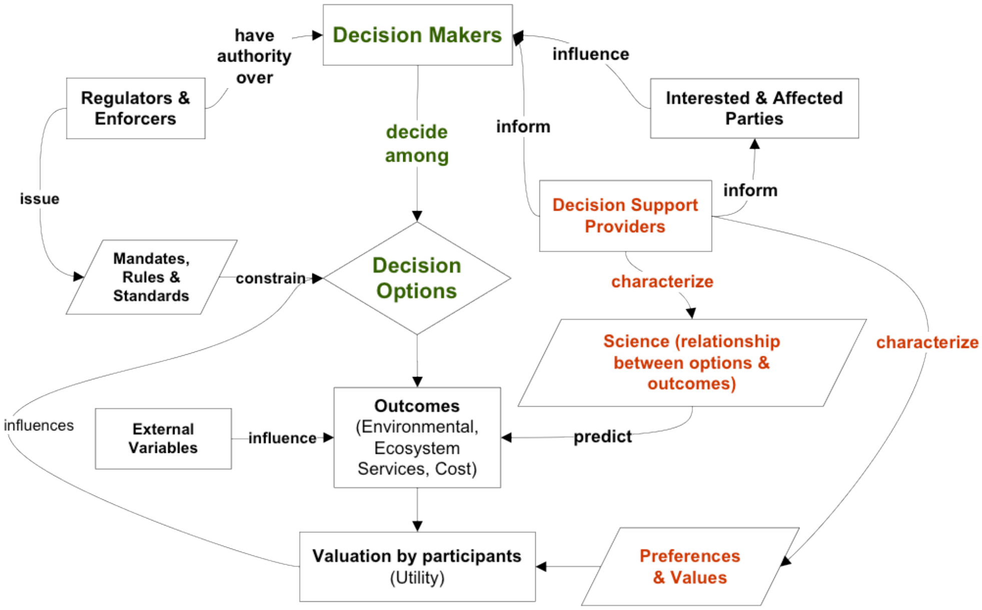


Figure 1: Example decision landscape diagram.

The scientific setting should also be addressed at this stage, so that the underlying facets of the probabilistic science-based models are also addressed. This information should be included in the decision diagram, or perhaps in a conceptual site model description and diagram.

Panel Session Example

Decision Landscape – Context

Consider a (fictitious) radioactive waste stream that is being considered for disposal at a specific radioactive waste disposal facility. The decision to be made is how and where to dispose of the waste within the system for optimal sustainable effect. Considerations include transport of radioactive contaminants to the accessible environment, either through infiltration of precipitation and transport of contamination to groundwater, or biotic and gaseous transport to the surface soils.

Regulatory, Social and Environmental landscape

The regulatory landscape includes DOE Orders and EPA and state environmental agency regulations or agreements, such as a Federal Facilities Agreement. These might apply to human health risk, ecological risk, groundwater, air emissions, and standards for owners and operators of hazardous waste treatment, storage and disposal facilities. Regulatory concerns might also address concepts associated with ALARA or CERCLA’s nine criteria. Waste disposal decisions might also invoke NEPA or NRDA regulations. The waste disposal site under consideration is remote, but there might be impacts to the nearest humans such as jobs, tourism, property values. The site is located in an environmentally hostile area, where humans have not lived before.

Stakeholder landscape

Stakeholder groups include DOE, the state environmental agency, EPA, Native Americans, and concerned citizens. Each stakeholder group probably has different concerns. Government agencies probably want to meet regulatory objectives; Native Americans might want to protect cultural resources, and might view any degradation of land, air and water as a concern; concerned citizens might identify protection of human health, effect on the local economy, and environmental justice as issues that matter to them. A social network analysis can reveal relationships between stakeholders as shown in Figure 2. Note that two groups are completely disengaged from the larger group. This analysis helps identify disconnects in the stakeholder network that might need to be addressed.

Scientific Setting and Conceptual Site Model

The conceptual site model for this example is set up assuming a simple trench or pit near-surface disposal. Climate and vegetation control water movement in the upper few meters of the native soil material. Water contents are low except during and after precipitation events. Evaporation is the dominant process for water movement except during precipitation events. However, precipitation can be sufficient to drive water down into the waste zone. Gaseous diffusion is possible for this waste stream. Contamination that is moved to the surface might be re-suspended and dispersed to other locations. Erosion impacts are considered unlikely because the site is returned to grade subsequent to disposal.

Step 2: Define objectives

Once the stakeholders understand the basic decision landscape, the next step is to define objectives. Value-focused thinking places the decision making focus on stakeholder values rather than decision alternatives. Consequently, stakeholder values or objectives play a central role and guide all phases of the decision process, including development of decision alternatives and the collection and analysis of the information needed to evaluate decision alternatives. This focus on objectives helps to ensure the decision process produces solutions that are transparent and traceable with respect to stakeholder and decision maker needs and preferences (i.e., values).

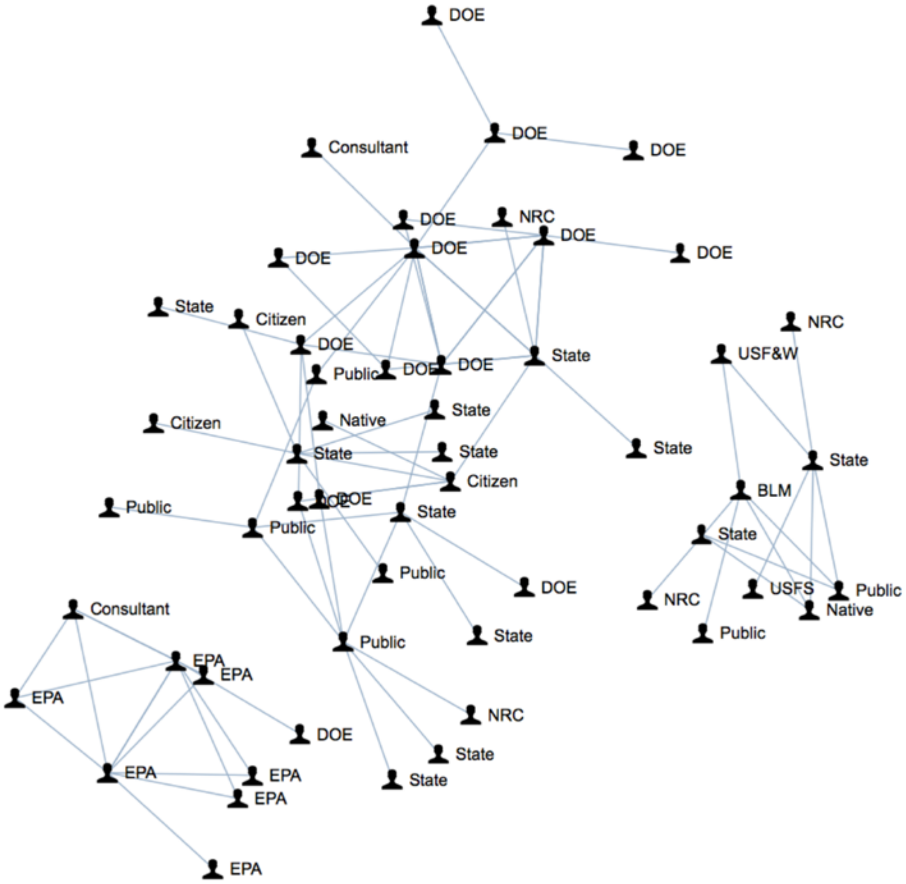


Figure 2: Example social network analysis.

Objectives Hierarchy

Stakeholder preferences and values are organized into an Objectives Hierarchy. An Objectives Hierarchy organizes the things stakeholders care about into layers or 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 determine what information to seek, helps explain decisions to others, and helps to determine a decision's importance and, consequently, how much time and effort it deserves.

An objective has a specific definition, it specifies what needs to be achieved and is structured as a short phrase of a verb and an objective. Examples include:

- Minimize environmental sustainability
- Satisfy regulatory compliance objectives
- Minimize population health impacts
- Minimize costs

Developing an objectives hierarchy is more of an art than a science. The intent is to help stakeholders think through all aspects of the problem and put all stakeholder concerns, desires, and preferences on the table for consideration. The stakeholders are encouraged to address what matters to them with respect to the environmental contamination or waste management problem at hand. For example, stakeholders might express concerns about the effect on human health, ecological health or systems, land values, costs of disposal. The art of identifying objectives involves several steps:

1. Write down all the stakeholder concerns that could be addressed for the specific decision (GiSdT provides a Scratchpad tool for collecting these general thoughts and concerns).
2. Convert these concerns into succinct objectives – this can be done directly with the stakeholders, but sometimes it is preferable to do that offline and bring the objectives back to the stakeholders for iteration; this depends on the complexity of the objectives).
3. Separate ends from measures to establish the fundamental objectives. Fundamental objectives are usually high-level objectives that might not be directly measurable. For example, minimize impact on human health might be a fundamental objective, whereas that might be measured through an objective that is minimize radiation dose.
4. Clarify what is meant by each objective. It is critically important that each objective is properly defined. Even the example in Step 3 to minimize radiation dose is not adequately defined – dose to whom? In what time frame? Unambiguous identification is critical to successful decision modeling, a sentiment that applies equally to the science-based and costs/value judgments modeling.
5. Test the objectives to see if they capture the interests of the stakeholders. Once the hierarchy is completed, it should be re-visited to make sure it properly captures every stakeholder value. This is an opportunity for iteration, although iteration is expected throughout the development of the objectives hierarchy. Note also, that the objectives hierarchy might be re-visited again after value functions and decision options are identified.

Once an objectives hierarchy is identified then 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. This is a key concept: science-based model elements that are studied, and which might involve data/information collection, prediction, analysis, etc., are directly tied to evaluating objectives and the resources needed to address these model elements are driven by this decision's objectives. Powerful computing capabilities available in a program such as ASCEM would be used only if the decision’s objectives indicate a need to refine a science-based model to the extent that high-performance computing is needed. With this paradigm shift, science-based models are built only to be as complex as necessary. Building the objectives hierarchy and defining measurable attributes is the cornerstone to making defensible decisions.

When eliciting objectives through this approach different stakeholders might prefer to start with a fundamental objective and break it down to arrive at measurable attributes, or they might prefer to start with a measurable attribute and back up to its fundamental objective. Following the example introduced in Step 1, eliciting some specific parts of the objectives hierarchy might look like the following:

1. Describe something that matters to you in how this problem is solved.
    a. *Stakeholder desire to protect family from radiation poisoning*?
2. Is radiation poisoning the only health concern?
    a. *Cancer is identified as a health concern.*
3. Does your concern about your family extent to others?.
    a. Yes, it extends to the local population because we are all potentially affected.
4. Does this extend beyond local residents?
    a. *Yes, it includes visitors*.
    b. Ask for specification about visitors and any groups of potentially exposed populations.
5. *How might health effects be measured*?
    a. Number of deaths, or hospital visits because of illness that are related to radiation.
6. *That's good, but the impact has already occurred. Can health effects be predicted instead*?
    a. Radiation dose is a potential measure that could predict future deaths/illnesses.

This is a simple example of what Scratchpad tool input might look like for capturing a subset of stakeholder concerns (Step 1 above). Now these notes need to be translated into an objectives hierarchy. Starting with a fundamental objective, this might look like the following:

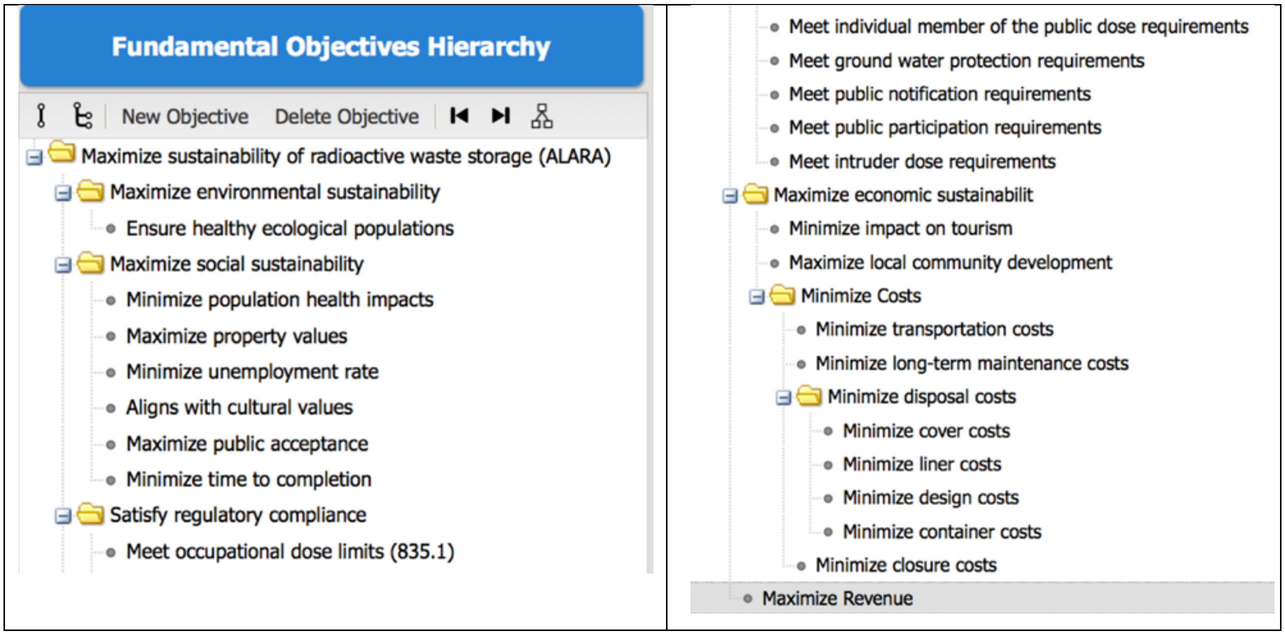
- Fundamental objective – Maximize social sustainability
- Secondary fundamental objective – Minimize population health impacts
- Measurable objective – Minimize amount of additional radiation exposure
- Measure – Radiation dose to the population.

Even this is not complete in that the specification is not unambiguous, at least because the population is not defined, and the measure of radiation dose is not provided. In addition, this could lead to arguments about the validity of dose as an appropriate measure of human health effects, depending on the stakeholders. However, this provides a simple example of how a part of the objectives hierarchy might be developed starting with a fundamental objective.

An example that goes in the opposite direction from measureable attribute to fundamental objective might produce an objectives hierarchy that looks like (presumably with a different stakeholder group):

- Measure – Cost of implementing cover design
- Measureable objective – minimize cover costs – *why*?
- Secondary fundamental objective – minimize disposal costs – *why*?
- Fundamental objective – part of minimizing overall costs – *why*?
    - Because the costs are paid for with taxpayer money.

An example objectives hierarchy used in the panel session is shown in Figure 3.



- Maximize sustainability of radioactive waste storage (ALARA)
  - Maximize environmental sustainability
    - Ensure healthy ecological populations
  - Maximize social sustainability
    - Minimize population health impacts
    - Maximize property values
    - Minimize unemployment rate
    - Aligns with cultural values
    - Maximize public acceptance
    - Minimize time to completion
  - Satisfy regulatory compliance
    - Meet occupational dose limits (835.1)
    - Meet individual member of the public dose requirements
    - Meet ground water protection requirements
    - Meet public notification requirements
    - Meet public participation requirements
    - Meet intruder dose requirements
  - Maximize economic sustainabilit
    - Minimize impact on tourism
    - Maximize local community development
    - Minimize Costs
      - Minimize transportation costs
      - Minimize long-term maintenance costs
      - Minimize disposal costs
        - Minimize cover costs
        - Minimize liner costs
        - Minimize design costs
        - Minimize container costs
      - Minimize closure costs
  - Maximize Revenue

Figure 3: **Example objectives hierarchy.**

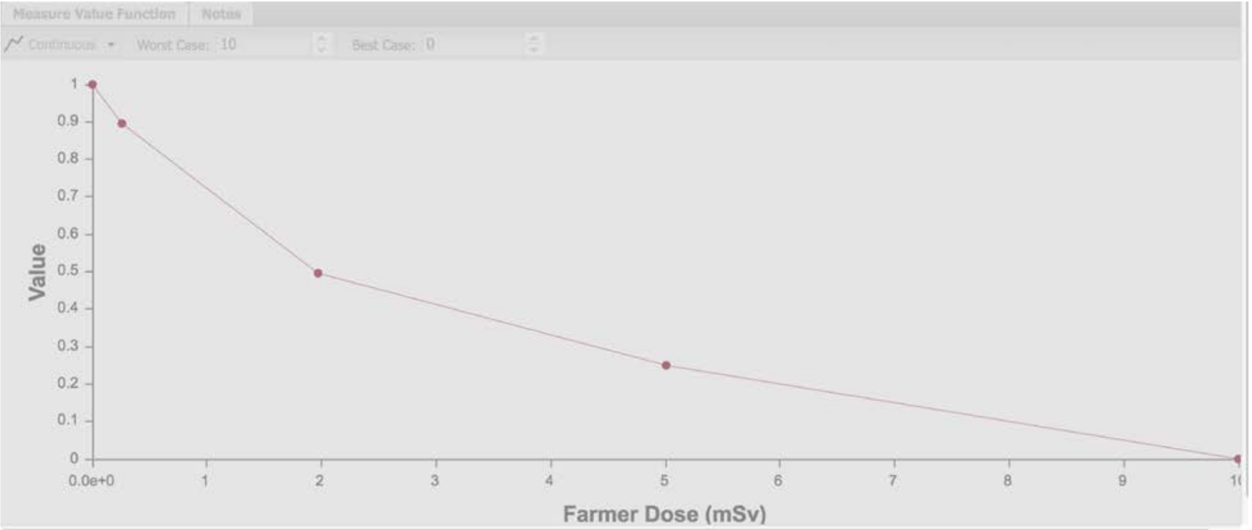
Specification of Value Functions

Once an objectives hierarchy is defined then each of the lowest level sub-objectives is associated with an attribute or measure by which the achievement of an objective can be measured. The next step is to specify value functions for each measureable objective. In the GiSdT implementation of SDM, value functions are normalized to a 0-1 scale. This helps avoid direct specification of dollar, or other cost-related values, to attributes that do not have obvious monetary value. It also allows measures to be combined and compared, and places each measure on a level playing field when considering objectives preference weighting.

Discussions on these types of value, or utility, functions in the literature suggest many different specification methods, with arguments both for and against many of the methods. Most discussions use monetary value as a starting point for explaining utility functions. The concept of risk aversion plays a prominent role, so that the utility of money is represented by a concave function. For example, when faced with the opportunity to take a 50-50 gamble to win \$100,000, or receive a guaranteed \$60,000, most people would take the \$60,000 guarantee. However, when faced with a similar option with only a \$30,000 guarantee it is not as obvious – some will take the \$30,000 and others will take the 50-50 chance at \$100,000. The difference depends on the level of risk aversion, which can be expressed as a utility function for money. The utility function for money is also assumed to be increasing on the positive real line – that is, more money is of greater value. However, the value diminishes with amount of money. As the amount of money increases, the level of indifference becomes greater so that utility functions for money tend to be concave on the positive real line (gain rather than loss).

The same type of approach can be used to compare the value of different levels of non-monetary factors. For example, a value function can be created for dose to exposed humans.

Some value functions were specified as part of the panel session – one for farmer dose, and one for total revenues. The example for farmer costs is presented in Figure 4, and shows decreasing value with increased dose.



Worst Case: 10

Best Case: 0

Figure 4: Example value function for a farmer dose endpoint.

Objectives preference weighting

There are two steps to specifying preference weighting – ranking followed by weighting. 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. This starts with presenting a hypothetical worst-case scenario – one that performs at the worst possible level for each attribute. The highest ranked attribute is selected as the attribute for which change from the worst case to the best case would result in the greatest beneficial change. The process continues, choosing attributes to move from worst to best case, resulting in a complete ranking of the attributes. The swing weight approach is not the only option for ranking attributes, but is fairly simple compared to other methods.

The user is then presented with pairs of successively ranked attributes and asks for a relative importance of the higher-ranked attribute. If $r_{i+1,i}$ is the relative importance of the (i+1)th-ranked attribute to the ith-ranked attribute, then n attribute ranks convert to importance weights as:

$$w_i = \frac{\prod_{j=1}^{i} r_{j,j-1}}{\sum_{k=1}^{n}\left(\prod_{j=1}^{k} r_{j,j-1}\right)}$$

(where $r_{1,0}$=1 for notational convenience). Note if there is difficulty choosing between two attributes in the ranking, a relative importance weight near 1 can be assigned, giving the two attributes nearly equal weight, and making the difference ineffectual. With complete specification of value functions and weights for the measurable attributes, the costs/value judgments side of the decision model is nearly complete. The remaining steps address identifying decision options and associating them with measurable attributes.

Step 3: Identify decision options

The value-focused philosophy of SDM provides a bottom-up rather than a top-down construction of decision options. Decision options are explicitly derived from the decision context and objectives. Decision options should have several characteristics [1, 6]:

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

The intent is that the options should be mutually exclusive so that direct comparison is possible without concern about interacting options. The measurable objectives identified in Step 2 are used as a path to development of decision options. Decision options that are not related to any of the measures cannot be evaluated. An example preliminary list of management options for the panel session example included:

- Engineering controls – container type, cover design, cover maintenance, waste burial depth, waste inventory
- Institutional controls
- Waste shipment options
- Public meetings.

The set of mutually exclusive decision options identified can also be combined under management scenarios so that combinations of options can be compared. These are termed management scenarios.

Step 4: Evaluate options

The decision options are formed from the objectives hierarchy. So far, this involves addressing the costs and value judgments side of a decision model. The options identified, or the management scenarios must be evaluated for their likelihood. Decisions are ultimately made based on a balance of likelihood with preferences that are expressed through the objectives, values, and preference weighting. This is where the science-based models enter the decision analysis system. It is most common to develop the science-based models first, but the purpose with this paradigm shift is to develop science-based models that help address the decision options that have been identified. That is, science-based modeling is performed with a clear purpose. The science-based models must be developed probabilistically so that uncertainty is being characterized and managed properly.

There is no limitation on the form of the science-based modeling, except that it should be probabilistic. GiSdT uses R (r-project.org) as its analytical engine, and native code can be written in R that performs science-based modeling. However, other programs are designed specifically for this purpose, and can be directly integrated with GiSdT. There are no limitations on which science-based codes could be integrated with GiSdT so that the complete decision analysis can be performed. Performance Assessment is often performed using GoldSim [9]. If more computing power is needed, then GiSdT could be integrated with the Advanced Simulation Capability for Environmental Modeling (ASCEM) [5], which is a modular, open source set of tools and a modeling workflow that supports robust and standardized assessments of performance and risk for DOE-EM cleanup and closure regulatory actions.

Evaluation of the options means providing results for each option. Results are expressed in terms of the measures that were identified earlier in the process. Science-based models in performance assessment usually focus only on the dose endpoints for various receptors. Here, the science-based models must address all measures. The decision analysis is an overall evaluation of all of the measures that are relevant for each decision option. This also means, for example, evaluating the performance of all of different cover design options, including cost and effectiveness. It also means evaluating transportation risk and costs, and the costs involved with institutional control options, and public participation. All measures identified must be evaluated with a corresponding science-based model.

Step 5: Take action

Once the models have been evaluated the remaining steps in the decision analysis process include:

a. Uncertainty analysis
b. Sensitivity analysis
c. Choosing the optimal decision option (or management scenario) or collecting more data/information (including model refinement as necessary)
d. Iterate if necessary

In the full iteration of decision modeling, uncertainty and sensitivity analysis is used to identify the main drivers for the decisions to be made. This is followed by making a decision (choosing the best option, or the best management scenario), or identifying a need to collect more information with subsequent iteration. Useful methods for sensitivity analysis are described in a companion WM2015 paper [4].

The action taken might be a final decision option, or it might be collection of more information/data. If the latter, then the need for iteration is indicated. This approach was taken to the low-level waste disposal performance assessments for the Nevada Test Site in 2006. The resulting iterations led to a more informed model, and the final decision on thickness of the evapotranspirative mono-fill cover was optimized, saving DOE substantial amounts of money, while maintaining the need to be protective of human health and the environment.

DISCUSSION

The panel session was conducted as a mock elicitation with primary focus on the values-based modeling side of a decision analysis. That is, it focused on the first three steps of the stakeholder engaged, structured decision making process. The panelists played the role of stakeholders, while the audience effectively played the role of public stakeholders. The panelists and audience provided some feedback, most of which was positive and was aimed at potential uses. A summary of the highlights follows:

- This has the potential to be a significant communication tool that could be used effectively to educate the public and stakeholders to the decision process.
- This approach could be valuable for gauging stakeholder involvement
- The approach provides the means to manage and tend to the emotion, complexity and technical challenges and to track all the “moving parts”.
- This approach could be used to compare over the life cycle of the mission, not just each project.
- Application to existing EIS’s would help the public understand our decision-development process. The tool allows soft science to be considered and weighted in the process.
- For NEPA, this approach would engage stakeholders much earlier in the process.
- This approach is more quantitative than other approaches that attempt to perform similar functions.
- Some help would be needed to facilitate this type of approach, at least for the first few cases.
- Clear potential in an environment of declining budgets and shorter decision-making time frames.
- Process of high potential value in complex systems with lots of moving parts.
- The tool’s transparency can draw people into the decision making process.
- Documenting all inputs in such a structured fashion is critical for knowledge transition management.
- This approach shows citizens that their concerns are not only heard and captured, but also valued.
- This has the potential to quantify stakeholder’s input and see now these inputs impact decisions. It could help blend what we have to do with what we can do.
- The paradigm shift moves from a transactional process to a SDM process that has iterations and dialogs that help build trust and form strong relationships among stakeholders.
- DOE considers the science-side and the stakeholders consider the alternatives. SDM can allow various insights from impacts on decisions when values are changed.

Some comments were also provided on the paradigm shift. For example, the paradigm shift was seen as one that moves towards starting with known factors and preferences and values instead of the technical solution; the focus is moved away from compliance based determinations only; probabilistic modeling is now placed in the right context and is required; ASCE could be used to help explain results of the science-based models that support this type of decision analysis; stakeholders engagement/education happens throughout the process; and, requires simulation that underscores the value of the SDM process.

Another comment that was made addressed the potential for enhancing regulations such as Sec. 3116 and 435.1. Some waste management regulations are currently undergoing revision – the time is ripe for inclusion of an approach like this. There were some concerns about complexity of the process, however, for solving complex problems, perhaps some complexity should be needed – after all, these are not simple problems that have simple solutions.   Some comments were also made that this approach to removing conservatism from science-based models might be difficult considering the current paradigm. The counterpoint is that the intent is not to remove conservatism, but to place it in the right context. The question remains, however, as to whether DOE is willing to be a change agent in this attempted paradigm shift. Fortunately, other agencies are already being change agents in this regard, in which case, DOE would be catching up to EPA, FDA and other agencies.

CONCLUSIONS

Overall, stakeholder engaged structured decision making integrates Value-Focused Thinking, Bayesian decision analysis, and environmental fate and transport modeling to provide for transparent, efficient and defensible environmental and waste management decisions. The paradigm shift is important for several reasons, not the least of which is from a technical perspective it is the right way to solve decision problems, and all problems are decision problems. In the current world of environmental and waste management, budgets are being reduced and there is a preference for shorter time frames to completion. However, completion is not achievable with the current paradigm, as many examples have shown. The current paradigm includes conservatism, and ineffective stakeholder engagement that often leads to redo. Effectively engaging stakeholder through SDM, and placing conservatism where it belongs in value judgments rather than science, can open the door to more effective decision making, saving DOE money while maintaining and improving the understanding of human health and environmental protection. In addition, 30 years of experience coupled with fantastic advances in technology should pave the way for a paradigm shift into more effective decision making. The bottom line is that the current approach is not affordable; it won’t support completion – a paradigm shift is needed. Advantages of the paradigm shift towards stakeholder engaged SDM include:

- Better decisions are made – technically defensible, transparent and traceable with thorough documentation of all inputs to the decision making process.
- Hurdles for upstream decisions are removed – e.g., nuclear energy.
- Saves money for DOE, hence for the government, tax payers, etc., in which case the money can be put to better uses

Other agencies have already moved in this direction to help solve complex environmental problems in areas such as brownfields, watershed management, coral reef management and food safety. Technology has advanced and these new ideas will continue to push to the fore. The suggested paradigm shift is happening. DOE can participate, and can use this approach to make more effective environmental and waste management decisions. The current round of revisions of DOE O 435.1 and NRC’s 10 CFR 61 would benefit from allowing for this paradigm shift, or at least to not be an obstacle. The regulations are not revised very often – it would be unfortunate to have to wait another generation to support this paradigm shift. Providing flexibility to continue to improve the decision making process would provide greater benefit to future generations than, for example, worrying about compliance periods.

Yes, it costs money to implement an approach like this (but all modeling approaches cost money), however, the savings from doing so are often enormous because success is more likely and complicated science-based modeling is more focused on actual decision needs. Stakeholder engaged SDM can help solve the challenging problems that remain, including management of complex new (and old) waste streams, site selection, licensing, and records of decision that are currently failing.

Next steps include building an awareness of this approach, continuing its development, finding case studies to apply and improve the approach, and, transferring the technology so that the paradigm shift and SDM approach is available for widespread use. . There are also some research needs that will need to be addressed, and continual improvement in application can be expected.

This paper and associated panel session primarily addresses one of the three aspects of a fully integrated approach to solving decision problems. The paradigm shift can be described as stakeholder engaged structured decision making, requiring values-focused thinking to set the stage for evaluation of decision options [1], a subsequent different approach to engaging stakeholders [3], and science-based modeling tools that can evaluate the decision options at the level of complexity needed to solve the problem [5].

This paradigm shift towards better (optimal) stakeholder engaged SDM using GiSdT provides smarter tools for solving complex problems. This will help the DOE enterprise make better decisions and focus limited resources on the most important problems. This SDM process is not a short cut, but a thorough vetting of the issues, risks and costs that go into determining best resolution of nuclear waste storage and cleanup decisions. The anticipated outcome of this process is a greater understanding and acceptance of the risks and associated costs that different levels of residual risk lead to in these decisions.

REFERENCES

1. Black, K., Black, P., Stockton, T., “A Paradigm Shift: An Introduction to Structured Decision Making for Sustainable Waste Management and Remediation,” Proceedings of the Waste Management 2015 Symposia, Phoenix AZ (March 2015)
2. Stockton, T., Black, P., Black, K., “GiSdT: An Open Source Software Integration of Decision Analysis and Stakeholder Judgment for Sustainable Waste Management,” Proceedings of the Waste Management 2015 Symposia, Phoenix AZ (March 2015)
3. Boucher, L., “What Does the Public Really Want when Engaging with the Nuclear Industry?” Proceedings of the Waste Management 2015 Symposia, Phoenix AZ (March 2015)
4. Black, P., Stockton, T., Duffy, P., “Modern Sensitivity Analysis,” Proceedings of the Waste Management 2015 Symposia, Phoenix AZ (March 2015)
5. Dixon, P., Freedman, V., Moulton, D., Freshley, M., Finsterle, S., Steefel, C., Wainwright, R., Seitz, R., Scheibe, T., Marble, J., “Advanced Simulation Capability for Environmental Management, Integrated Toolsets and Simulator to Enhance Public Communication”, Proceedings of the Waste Management 2015 Symposia, Phoenix AZ (March 2015).
6. Gregory, R., Failing, L.,Harstone, M., Long, G., McDaniels, T., and Ohlson, D., “Structured Decision Making: A Practical Guide to Environmental Management Choices”, Wiley-Blackwell, 2012.
7. Keeney, R., “Value-Focused Thinking: A Path to Creative Decision Making”. Cambridge, MA: Harvard University Press, 1992.
8. Rehr, A, Small, M., Bradley, P., Fisher, W., Vega, A, Black , K., Stockton, T., “A Decision Support Framework for Science-Based, Multi-Stakeholder Deliberation: A Coral Reef Example”. Environmental Management, December 2012, Volume 50, Issue 6, pp 1204-1218.
9. GoldSim Technology Group, “GoldSim: Monte Carlo Simulation Software for Decision and Risk Analysis”, www.goldsim.com, Version 11.2, 2015.