MULTI-CRITERIA DECISION ANALYSIS: A FRAMEWORK FOR STRUCTURING REMEDIAL DECISIONS AT CONTAMINATED SITES

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Abstract

Decision-making in environmental projects is typically a complex and confusing exercise, characterized by trade-offs between socio-political, environmental, and economic impacts. Cost-benefit analyses are often used, occasionally in concert with comparative risk assessment, to choose between competing project alternatives. The selection of appropriate remedial and abatement policies for contaminated sites, land-use planning and other regulatory decision-making problems for contaminated sites involves multiple criteria such as cost, benefit, environmental impact, safety, and risk. Some of these criteria cannot easily be condensed into a monetary value, which complicates the integration problem inherent to making comparisons and trade-offs. Even if it were possible to convert criteria rankings into a common unit this approach would not always be desirable since stakeholder preferences may be lost in the process. Furthermore, environmental concerns often involve ethical and moral principles that may not be related to any economic use or value.

Considerable research in the area of multi criteria decision analysis (MCDA) has made available practical methods for applying scientific decision theoretical approaches to multi-criteria problems. However, these methods have not been formalized into a framework readily applicable to environmental projects dealing with contaminated and disturbed sites where risk assessment and stakeholder participation are of crucial concern. This paper presents a review of available literature on the application of MCDA in environmental projects. Based on this review, the paper develops a decision analytic framework specifically tailored to deal with decision making at contaminated sites.

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1. Current and Evolving Decision-Analysis Methodologies

Environmental decisions are often complex, multi-faceted, and involve many different stakeholders with different priorities or objectives – presenting exactly the type of problem that behavioral decision research shows humans are typically quite bad at solving, unaided. Most people, when confronted with such a problem will attempt to use intuitive or heuristic approaches to simplify complexity until the problem seems more manageable. In the process, important information may be lost, opposing points of view may be discarded, elements of uncertainty may be ignored -- in short, there are many reasons to expect that, on their own, individuals (either lay or expert) will often experience difficulty making informed, thoughtful choices about complex issues involving uncertainties and value tradeoffs (McDaniels et al., 1999).

Moreover, environmental decisions typically draw upon *multidisciplinary* knowledge bases, incorporating natural, physical, and social sciences, medicine, politics, and ethics. This fact, and the tendency of environmental issues to involve shared resources and broad constituencies, means that *group* decision processes are called for. These may have some advantages over individual processes: more perspectives may be put forward for consideration, the chances of having natural systematic thinkers involved is higher, and groups may be able to rely upon the more deliberative, well-informed members. However, groups are also susceptible to the tendency to establish entrenched positions (defeating compromise initiatives) or to prematurely adopt a common perspective that excludes contrary information -- a tendency termed “group think.” (McDaniels et al., 1999).

For environmental management projects, decision makers may currently receive four types of technical input: modeling/monitoring, risk analysis, cost or cost-benefit analysis, and stakeholders’ preferences (Figure 1a). However, current decision processes typically offer little guidance on how to integrate or judge the relative importance of information from each source. Also, information comes in different forms. While modeling and monitoring results are usually presented as quantitative estimates, risk assessment and cost-benefit analyses incorporate a higher degree of qualitative judgment by the project team. Only recently have environmental modeling (such as fate and transport models) and formalized risk assessment been coupled to present partially integrated analyses to the decision-maker (e.g., Army Risk Assessment Modeling project, ARAMS (Dortch, 2000). Structured information about stakeholder preferences may not be presented to the decision-maker at all, and may be handled in an *ad hoc* or subjective manner that exacerbates the difficulty of defending the decision process as reliable and fair. Moreover, where structured approaches *are* employed, they may be perceived as lacking the flexibility to adapt to localized concerns or faithfully represent minority viewpoints. A systematic methodology to combine these inputs with cost/benefit information and stakeholder views to rank project alternatives has not yet been developed. As a result, the decision maker may not be able to utilize all available and necessary information in choosing between identified remedial and abatement alternatives.

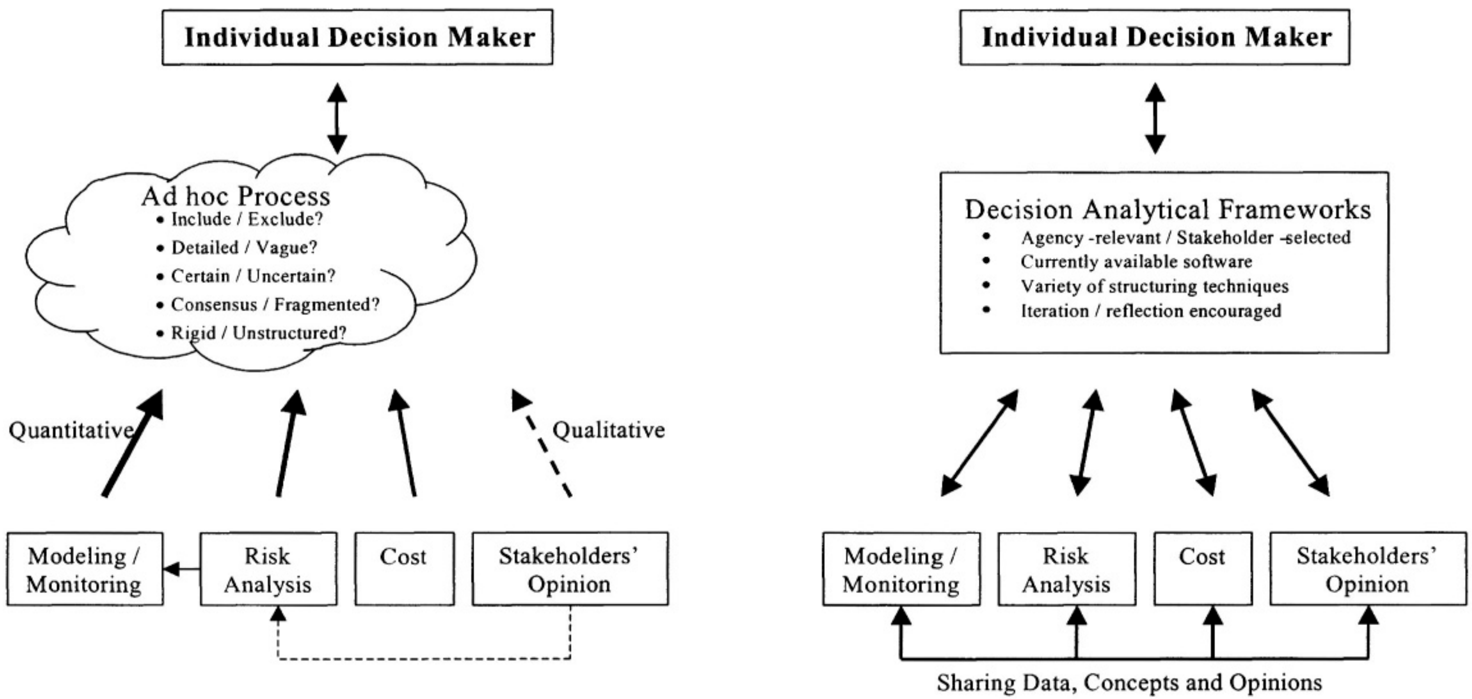
In response to current decision-making challenges, this paper develops a systematic framework for synthesizing quantitative and qualitative information that builds on the recent efforts of several government agencies and individual scientists to

implement new concepts in decision analysis and operations research. This will help to both facilitate analysis and provide for more robust treatment of stakeholder concerns. The general trends in the field are reflected in Figure 1b. Decision analytical frameworks may be tailored to the needs of the individual decision maker or relate to multiple stakeholders. For individual decision-makers, risk-based decision analysis quantifies value judgments, scores different project alternatives on the criteria of interest, and facilitates selection of a preferred course of action. For group problems, the process of quantifying stakeholder preferences may be more intensive, often incorporating aspects of group decision-making. One of the advantages of an MCDA approach in group decisions is the capacity for calling attention to similarities or potential areas of conflict between stakeholders with different views, which results in a more complete understanding of the values held by others. In developing this framework, the paper will draw from existing literature on environmental applications of multi criteria decision theory and regulatory guidance developed by the US and international agencies.

2. MCDA Methods and Tools

MCDA methods evolved as a response to the observed inability of people to effectively analyze multiple streams of dissimilar information. There are *many* different MCDA methods. They are based on different theoretical foundations such as optimization, goal aspiration, or outranking, or a combination of these:

- **Optimization models** employ numerical scores to communicate the merit of one option in comparison to others on a single scale. Scores are developed from the performance of alternatives with respect to an individual criterion and then aggregated into an overall score. Individual scores may be simply added up or averaged, or a weighting mechanism can be used to favor some criteria more heavily than others. Typically, (but not always, depending upon the sophistication of the objective function) good performance on some criteria can compensate for poor performance on others. Normalizing to an appropriate single scale may be problematic. Consequently, optimization models are best applied when objectives are narrow, clearly defined, and easily measured and aggregated. Considerable research and methods development has been done on multiobjective optimization. This work has mostly involved finding the “Pareto frontier”, along which no further improvements can be made in any of the objectives without making at least one of the other objectives worse (Diwekar and Small, 2002).
- **Goal aspiration,** reference level, or threshold models rely on establishing desirable or satisfactory levels of achievement for each criterion. These processes seek to discover options that are closest to achieving, but not always surpassing, these goals. When it is impossible to achieve all stated goals, a goal model can be cast in the form of an optimization problem in which the decision maker attempts to minimize the shortfalls, ignoring exceedances. To this extent, overperformance on one criterion may not compensate for underperformance on



a. Current Decision-Making Process

b. Evolving Decision-Making Process

Figure 1: Current and evolving decision -making processes for contaminated sediment management.

others. Alternatively, the decision maker may seek to satisfy as many of the goals as possible (even if only just barely) and ignore the fact that some performance metrics may be *very* far from target levels. Goal models are most useful when all the relevant goals of a project cannot be met at once.

- **Outranking models** compare the performance of two (or more) alternatives at a time, initially in terms of each criterion, to identify the extent to which a preference for one over the other can be asserted. In aggregating preference information across all relevant criteria, the outranking model seeks to establish the strength of evidence favoring selection of one alternative over another -- for example by favoring the alternative that performs the best on the greatest number of criteria. Outranking models are appropriate when criteria metrics are *not* easily aggregated, measurement scales vary over wide ranges, and units are incommensurate or incomparable. Like most MCDA methods, outranking models are *partially* compensatory (Guitouni and Martel 1998).

The common purpose of these diverse methods is to be able to evaluate and choose among alternatives based on multiple criteria using systematic analysis that overcomes the observed limitations of unstructured individual and group decision-making. Different methods require different types of raw data and follow different optimization algorithms. Some techniques rank options, some identify a single optimal alternative, some provide an incomplete ranking, and others differentiate between acceptable and unacceptable alternatives.

An overview of four principal MCDA approaches is provided in the remainder of this section. A more detailed analysis of the theoretical foundations of these methods and their comparative strengths and weaknesses can be found in Belton and Stewart (2002) and other references.

2.1 ELEMENTARY METHODS

Elementary methods are intended to reduce complex problems to a singular basis for selection of a preferred alternative. Competing decision criteria may be present, but intercriteria weightings are not required. For example, an elementary goal aspiration approach may rank alternatives in relation to the total number of performance thresholds met or exceeded. While elementary approaches are simple and analysis can, in most cases, be executed without the help of computer software, these methods are best suited for single-decision maker problems with few alternatives and criteria – a condition that is rarely characteristic of environmental challenges.

2.1.1. Pros and Cons Analysis A Pros and Cons Analysis is a qualitative comparison method in which experts identify the qualities and defects of each alternative. The lists of pros and cons are compared to one another for each alternative, and the alternative with the strongest pros and weakest cons is selected. Pros and Cons Analysis is suitable for simple decisions with few alternatives (2 to 4) and few discriminating criteria (1 to 5) of approximately equal value. It can be implemented rapidly. (DOE, 2001) Other methods are based on the Pros and Cons concept, including SWOT Analysis and Force Field Analysis. SWOT stands for Strengths, Weaknesses, Opportunities, and Threats. SWOT analysis helps reveal changes that can be usefully made. In Force Field Analysis

the viability of a project is evaluated by comparing the forces for and against the project.

2.1.2. Maximin and Maximax Methods The maximin method is based upon a strategy that seeks to avoid the worst possible performance – or "maximizing" the poorest ("minimal") performing criterion. This is achieved by assigning total importance to the criteria in which an alternative performs the worst, ranking all alternatives by the strength of their *weakest* attribute. The alternative for which the score of its weakest attribute is the highest is preferred. In multi-attribute decision-making the maximin method can be used only when all attributes are comparable so that they can be measured on a common scale, which may present a serious limitation. An analogous strategy called *maximax* ranks alternatives solely by their *best* performing criterion. Maximin and minimax are noncompensatory, in that individual alternative performance is judged on the basis of a single criterion (although different criteria may be selected for different alternatives). Minimax and minimin methods also exist. Their names make their underlying concepts self-explanatory.

2.1.3. Conjunctive and Disjunctive Methods The conjunctive and disjunctive methods are non-compensatory, goal aspiration screening methods. They do not require attributes to be measured in commensurate units. These methods require satisfactory (in comparison with a predefined threshold) rather than best possible performance in each attribute -- i.e. if an alternative passes the screening, it's acceptable. The underlying principle of the conjunctive method is that an alternative must meet a minimum cutoff level (called a performance threshold) for *all* attributes. The disjunctive method is a complementary method. It requires that an alternative should exceed the given thresholds for at least *one* attribute. These simple screening rules can be used to select a subset of alternatives for analysis by other, more complex decision-making tools, or provide a basis for selection in and of themselves as in a strategy called Elimination by Aspects. In this approach, performance criteria are ordered in terms of importance. Alternatives that fail to meet the most important threshold level are discarded. Remaining alternatives are then tested against the second most important criteria, and on down. The last alternative to be discarded (in the event no alternative meets *all* criteria) is preferred.

2.1.4. Lexicographic Method A lexicographic analysis of any problem involves a sequential elimination process that is continued until either a unique solution is found or all the problems are solved. In the lexicographic decision-making method attributes are first rank-ordered in terms of importance. The alternative with the best performance on the most important attribute is chosen. If there are ties with respect to this attribute (which is quite likely if many alternatives are considered), the performance of the tied alternatives on the next most important attribute will be compared, and so on, till a unique alternative is found.

It should be noted that in multi-attribute decision-making problems with few alternatives, quantitative input data, and negligible uncertainty, the lexicographic method ends up becoming a selection method based on a single attribute.