Chapter 35 Appendix A: Multi-Criteria Decision Analysis

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A detailed analysis of the theoretical foundations of different MCDA methods and their comparative strengths and weaknesses is presented in Belton and Stewart (2002). MCDA methods utilize a decision matrix to provide a systematic analytical approach for integrating risk levels, uncertainty, and valuation, which enables evaluation and ranking of many alternatives. MCDA overcomes the limitations of less structured methods such as comparative risk assessment (CRA), which suffers from the unclear way in which it combines performance on criteria (see Bridges et al. 2005 for more information on CRA). Within MCDA, almost all methodologies share similar steps of organization and decision matrix construction, but each methodology synthesizes information differently (Yoe 2002). Different methods require diverse types of value information and follow various optimization algorithms. Some techniques rank options, some identify a single optimal alternative, some provide an incomeplete ranking, and others differentiate between acceptable and unacceptable alternatives.

Elementary MCDA methods can be used to reduce complex problems to a singular basis for selection of a preferred alternative. However, these methods do not necessarily weight the relative importance of criteria and combine the criteria to produce an aggregate score for each alternative. While elementary approaches are simple and 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 projects.

Table A1 summarizes a number of more sophisticated MCDA methods. Multi-attribute utility theory (MAUT), multi-attribute value theory (MAVT), and the analytical hierarchy process (AHP) are more complex methods that use optimization algorithms, whereas outranking eschews optimization in favor of a dominance approach. The optimization approaches employ numerical scores to communicate the merit of each option on a single scale. Scores are developed from the performance of alternatives with respect to individual criteria and then aggregated into an overall score. Individual scores may be simply summed or averaged, or a weighting mechanism can be used to favor some criteria more heavily than others. The goal of MAUT is to find a simple expression for the net benefits of a decision. Through the use of utility or value functions, the MAUT method transforms diverse criteria into one common scale of utility or value. MAUT relies on the assumptions that the decision-maker is rational (preferring more utility to less utility, for example), that the decision-maker has perfect knowledge, and that the decision-maker is consistent in his judgments. The goal of decision-makers in this process is to maximize utility or value. Because poor scores on criteria can be compensated for by high scores on other criteria, MAUT is part of a group of MCDA techniques known as "compensatory" methods.

Similar to MAUT, AHP (Saaty 1994) aggregates various facets of the decision problem using a single optimization function known as the objective function. The goal of AHP is to select the alternative that results in the greatest value of the objective function. Like MAUT, AHP is a compensatory optimization approach. However, AHP uses a quantitative comparison method that is based on pair-wise comparisons of decision criteria, rather than utility and weighting functions. All individual criteria must be paired against all others and the results compiled in matrix form. For example, in examining the choices in the selection of a non-lethal weapon, the AHP method would require the decision-maker to answer questions such as, "With respect to the selection of a weapon alternative, which is more important, the efficiency or the reduction of undesired effects (e.g., health impacts)?" The user uses a numerical scale to compare the choices and the AHP method moves systematically through all pair-wise comparisons of criteria and alternatives. The AHP technique thus relies on the supposition that humans are more capable of making relative judgments than absolute judgments. Consequently, the rationality assumption in AHP is more relaxed than in MAUT.

Unlike MAUT and AHP, outranking is based on the principle that one alternative may have a degree of dominance over another (Kangas et al. 2001). Dominance occurs when one option performs better than another on at least one criterion and no worse than the other on all criteria (ODPM 2004). However, outranking techniques do not presuppose that a single best alternative can be identified. 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. Outranking techniques then aggregate the preference information across all relevant criteria and seek to establish the strength of evidence favoring selection of one alternative over another. For example, an outranking technique may entail favoring the alternative that performs the best on the greatest number of criteria. Thus, outranking techniques allow inferior performance on some criteria to be compensated for by superior performance on others. They do not necessarily, however, take into account the magnitude of relative underperformance in a criterion versus the magnitude of over-performance in another criterion. Therefore, outranking models are known as “partially compensatory.” Outranking techniques are most appropriate when criteria metrics are not easily aggregated, measurement scales vary over wide ranges, and units are incommensurate or incomparable (Seager 2004).

Table A1. Comparison of Critical Elements, Strengths and Weaknesses of Several Advanced MCDA Methods: MAUT, AHP, and Outranking (after [19]).

Method	Important elements	Strengths	Weaknesses
Multi-attribute utility theory	• Expression of overall performance of an alternative in a single, non-monetary number representing the utility of that alternative • Criteria weights often obtained by directly surveying stakeholders	• Easier to compare alternatives whose overall scores are expressed as single numbers • Choice of an alternative can be transparent if highest scoring alternative is chosen • Theoretically sound — based on utilitarian philosophy • Many people prefer to express net utility in non-monetary terms	• Maximization of utility may not be important to decision makers • Criteria weights obtained through less rigorous stakeholder surveys may not accurately reflect stakeholders' true preferences • Rigorous stakeholder preference elicitations are expensive
Analytical hierarchy process	• Criteria weights and scores are based on pairwise comparisons of criteria and alternatives, respectively	• Surveying pairwise comparisons is easy to implement	• The weights obtained from pairwise comparison are strongly criticized for not reflecting people's true preferences • Mathematical procedures can yield illogical results. For example, rankings developed through AHP are sometimes not transitive

Method	**Important elements**	**Strengths**	**Weaknesses**
Outranking	● One option outranks another if : 1. “it outperforms the other on enough criteria of sufficient importance (as reflected by the sum of criteria weights)” and 2. it “is not outperformed by the other in the sense of recording a significantly inferior performance on any one criterion” ● Allows options to be classified as “incomparable”	● Does not require the reduction of all criteria to a single unit ● Explicit consideration of possibility that very poor performance on a single criterion may eliminate an alternative from consideration, even if that criterion’s performance is compensated for by very good performance on other criteria	● Does not always take into account whether over-performance on one criterion can make up for under-performance on another ● The algorithms used in outranking are often relatively complex and not well understood by decision makers

Example Ahp Application Framework

As an illustrative example of the analytical hierarchy process, consider the selection of a harmful algal bloom management strategy. Three options are available to the hypothetical managers:

- Algaecides
- Flushing
- Detoxification

The first step is to decide upon the objectives or criteria by which the alternative management techniques will be measured. As an example, we select the following criteria: (1) the strategy's human health impacts, (2) its environmental impacts, and (3) its social impacts.

The second step is to weight the importances of these criteria for the decision maker. Although in this simple scenario it would be possible to assign weights directly, in many practical applications it may be difficult because of the multitude of criteria and subcriteria that the decision maker may face. Therefore, in AHP, the decision-maker does not give importance weightings directly; rather, the category weightings are derived from a series of relative judgments. In this scenario, the decision-maker has input three relative judgments, in the form of weightings ratios. He has, for example, weighted human health impacts as four times more important than social impacts (see Table A2). From these relative weightings, AHP derives normalized weightings for the three criteria (see Table A3).

Table A2. Relative importance weightings, in the ratio form of row element / column element.

Main criteria table	Human Health Impacts	Environmental Impacts	Social Impacts
Human Health Impacts		4.0	4.0
Environmental Impacts			1.0
Social Impacts			

Table A3. Importance weightings for main criteria categories.

Main criteria weightings	
Human Health Impacts	0.667
Environmental Impacts	0.167
Social Impacts	0.167

Additionally, even in this simple case, because the main criteria categories are too broad to be used directly in evaluating management alternatives, sub-criteria within each of these categories should be developed. Within the Human Health Impacts category, for instance, one might consider drinking water quality, dermal effects, and inhalation effects. Similarly, sub-criteria may be developed for the other two criteria categories – such as the strategy's effects on fish, its birds, and mammals, or its cost and public acceptability (see Table A4). Sub-criteria are compared and weighted in a pairwise manner similar to that for the main criteria (see Table A5, Table A6, and Table A7).

Table A4. Sub-criteria for each main criteria category.

Goal: Identify best management techniques for harmful algal blooms

Main criteria category	**Sub-criteria**
Human Health Impacts	• Drinking water quality • Dermal effects • Inhalation effects
Environmental Impacts	• Effects on fish • Effects on birds • Effects on mammals
Social Impacts	• Cost • Public acceptability

Table A5. Importance weightings for Human Health Impacts sub-criteria.

Human Health Impacts sub-table	Drinking water quality	Dermal effects	Inhalation effects
Drinking water quality		7.0	5.0
Dermal effects			1.0
Inhalation effects			

Table A6. Importance weightings for Environmental Impacts sub-criteria.

Environmental Impacts sub-table	Effects on fish	Effects on birds	Effects on mammals
Effects on fish		1.0	7.0
Effects on birds			8.0
Effects on mammals			

Table A7. Importance weightings for Social Impacts sub-criteria.

Social Impacts sub-table	Cost	Public acceptability
Cost		6.0
Public acceptability		

Once relative weightings have been given for each of the sub-criteria, normalized weightings may be calculated for use in scoring different harmful algal bloom management alternatives (see breakdown in Table A8).

Table A8. Importance weightings for both main criteria categories and embedded sub-criteria.

Goal: Select harmful algal bloom management response	**Weighting**	**Sub-weighting**
Human Health Impacts	0.667	
• Drinking water quality		0.747
• Dermal effects		0.119
• Inhalation effects		0.134
Environmental Impacts	0.167	
• Effects on fish		0.458
• Effects on birds		0.479
• Effects on mammals		0.063
Social Impacts	0.167	
• Cost		0.857
• Public acceptability		0.143

The third step is to measure relative performance of each management option on each criteria. Again, the decision-maker inputs a relative ranking – only now it is a preference ranking between alternatives rather than an importance ranking among criteria. If a quantitative answer is not given, a qualitative statement may be transformed into a numerical value through a standardized system (i.e. the numbers 1, 3, 5, 7, and 9 correspond to the judgments “equally important,” “moderately more,” “strongly more,” “very strongly more,” and “extremely more,” respectively). Once the decision-maker gives inputs for each alternative under each sub-criteria, he may use the previously obtained weightings to calculate scores for each main criteria, followed by an overall score for each alternative (see Table A9). The highest scoring alternative is, according to the rankings and preferences given by the decision-maker throughout the analytic hierarchy process, the best strategy for the situation.

Table A9. Score breakdown for example decision.

Goal: Select harmful algal bloom management response	**Algaecides**	**Flushing**	**Detoxification**
Human Health Impacts	**0.061**	**0.332**	**0.607**
• Drinking water quality	0.061	0.353	0.586
• Dermal effects	0.060	0.249	0.691
• Inhalation effects	0.062	0.285	0.653
Environmental Impacts	**0.779**	**0.112**	**0.109**
• Effects on fish	0.783	0.174	0.043
• Effects on birds	0.778	0.042	0.180
• Effects on mammals	0.761	0.191	0.048
Social Impacts	**0.100**	**0.320**	**0.581**
• Cost	0.089	0.323	0.588
• Public acceptability	0.163	0.297	0.540
OVERALL SCORE	**0.187**	**0.293**	**0.520**

Many software packages exist to assist the decision-maker with implementation of the above process.

Framework Effectiveness

Effective decision-making requires an explicit structure for jointly considering the environmental, ecological, technological, economic, and socio-political factors relevant to evaluating alternatives and making a decision. Integrating this heterogeneous information with respect to human aspirations and technical applications demands a systematic and understandable framework to organize the people, processes, and tools for making a structured and defensible decision. Based on our review of MCDA, we have synthesized our understanding into a systematic decision framework (Fig. A1). This framework is intended to provide a generalized road map to the decision-making process.

Having the right combination of people is the first essential element in the decision process. The activity and involvement levels of two basic groups of people (decision-makers and scientists & engineers) are symbolized in Fig A1 by dark lines for direct involvement and dashed lines for less direct involvement. While the actual membership and the function of these groups may overlap or vary, the roles of each are essential in maximizing the utility of human input into the decision process. Each group has its own way of viewing the world, its own method of envisioning solutions, and its own societal responsibility. Policy- and decision-makers spend most of their effort defining the problem context and the overall constraints on the decision. In addition, they may have responsibility for the selection of the final decision and its implementation. Scientists and engineers have the most focused role in that they provide the measurements or estimations of the desired criteria that determine the success of various alternatives. While they may take a secondary role as decision-makers, their primary role is to provide the technical input as necessary in the decision process.

The framework places process in the center (Fig. A1). While it is reasonable to expect that the decision-making process may vary in specific details among regulatory programs and project types, emphasis should be given to designing an adaptable structure so that participants can modify aspects of the project to suit local concerns, while still producing a structure that provides the required outputs. The process depicted follows two basic themes: 1) generating alternatives, success criteria, and value judgments and 2) ranking the alternatives by applying the value weights. The first part of the process generates and defines choices, performance levels, and preferences. The latter section methodically prunes non-feasible alternatives by first applying screening mechanisms (for example, overall cost, technical feasibility, possible undesired consequences, or general societal acceptance) followed by a more detailed ranking of the remaining options by decision analytical techniques (AHP, MAUT, outranking) that utilize the various criteria levels generated by tools such as modeling, monitoring, or stakeholder surveys.

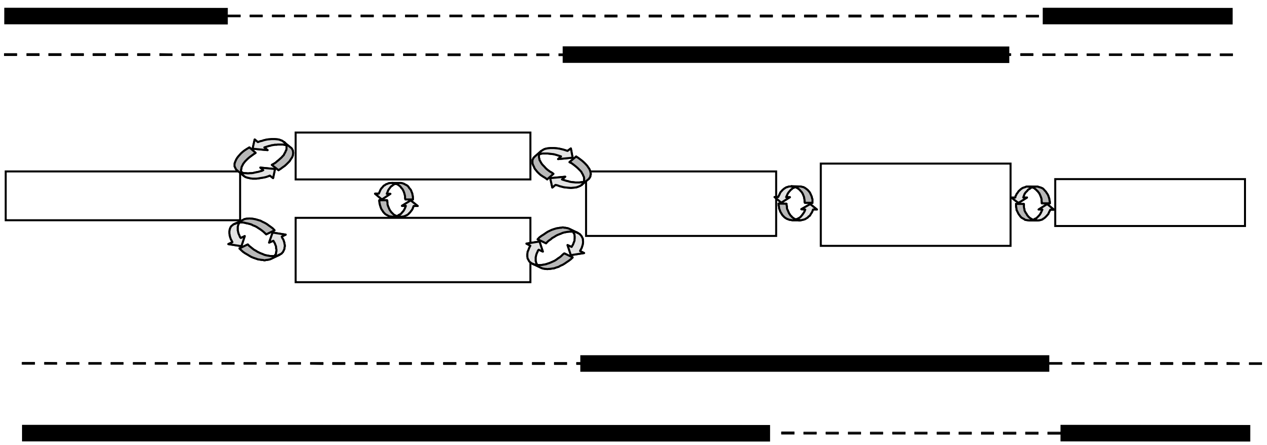

Fig. A1. General MCDA framework. Solid lines symbolize direct group involvement; dashed lines symbolize less direct involvement.

As shown in Fig. A1, the tools used within group decision-making and scientific research are essential elements of the overall decision process. As with people, the applicability of the tools is symbolized by solid lines (direct or high utility) and dotted lines (indirect or lower utility). Decision analysis tools help to generate and map value judgments into organized structures that can be linked with the other technical tools from risk analysis, modeling and monitoring, and cost estimations. Decision analysis software can also provide useful graphical techniques and visualization methods to express the gathered information in understandable formats. When changes occur in the requirements or decision process, decision analysis tools can respond efficiently to reprocess and iterate with the new inputs. The framework depicted in Fig. A1 provides a focused role for the detailed scientific and engineering efforts invested in experimentation, monitoring, and modeling that provide the rigorous and defendable details for evaluating criteria performance under various alternatives. This integration of decision and scientific and engineering tools allows each to have a unique and valuable role in the decision process without attempting to apply either type of tool beyond its intended scope.

As with most other decision processes, it is assumed that the framework in Fig. A1 is iterative at each phase and can be cycled through many times in the course of complex decision-making. A first-pass effort may efficiently point out challenges that may occur or modeling studies that should be initiated. As these challenges become more apparent, one iterates again through the framework to explore and adapt the process to address the more subtle aspects of the decision, with each iteration giving an indication of additional details that would benefit the overall decision.

Conclusions

The end result of the application of multi-criteria decision analysis is a comprehensive, structured process for selecting the optimal alternative in any given situation, drawing from stakeholder preferences and value judgments as well as scientific modeling and risk analysis. This structured process would be of great benefit to decision-making for homeland security, where there is currently no structured approach for making justifiable and transparent decisions with explicit trade-offs between social and technical factors. The MCDA framework links technological performance information with decision criteria and weightings elicited from decision-makers, allowing visualization and quantification of the trade-offs involved in the decision-making process. As demonstrated above, it is of great utility in applications such as management techniques for HABs.

Chapter 35 Appendix A References

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