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Application of Multicriteria Decision Analysis Tools to Two Contaminated Sediment Case Studies

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ABSTRACT

Environmental decision making is becoming increasingly more information intensive and complex. Our previous work shows that multicriteria decision analysis (MCDA) tools offer a scientifically sound decision analytical framework for environmental management, in general, and specifically for selecting optimal sediment management alternatives. Integration of MCDA into risk assessment and sediment management may require linkage of different models and software platforms whose results may lead to somewhat different conclusions. This paper illustrates the application of 3 different MCDA methods in 2 case studies involving contaminated sediment management. These case studies are based on real sediment management problems experienced by the US Army Corps of Engineers and other stakeholders in New York/New Jersey Harbor, USA, and the Cocheco River Superfund Site in New Hampshire, USA. Our analysis shows that application of 3 different MCDA tools points to similar management solutions no matter which tool is applied. MCDA tools and approaches were constructively used to elicit the strengths and weaknesses of each method when solving the problem.

Keywords: Environmental policy   Multicriteria decision analysis   Risk assessment   Sediments

INTRODUCTION

Environmental decision-making strategies over the past several decades have evolved into increasingly more sophisticated approaches, including expert judgment, cost–benefit analysis, toxicological risk assessment, comparative risk assessment, and many methods for incorporating public and stakeholder values. This evolution has led to an improved array of decision-making aides, including the development of multicriteria decision analysis (MCDA) tools that offer a scientifically sound decision analytical framework. Both the existence of different MCDA methods and the availability of corresponding software contribute to the possibility of practical implementation of these methods. However, many different MCDA methods may be utilized for analysis of an applied problem (Tecle 1992; Salminen et al. 1998; Belton and Steward 2002), and investigation is needed into the effects of using various methods, especially when recommendations concerning implementation of each method are ambiguous.

The objective of this paper is to simultaneously apply several different MCDA tools to the same environmental management problem and to analyze differences in the outputs of different MCDA methods. Two case studies based on real sediment management problems experienced by the US Army Corps of Engineers and other stakeholders in New York/New Jersey Harbor, USA, and the Cocheco River Superfund Site in New Hampshire, USA, were selected and analyzed using 3 MCDA methods: Analytical hierarchy process (AHP), outranking, and multiattribute value theory (MAVT). In our previous studies, we developed a general framework for MCDA application for sediment management (Kiker et al. 2005; Linkov et al. 2005) and developed a multidisciplinary review of existing decision-making approaches and MCDA methods applicable to contaminated sediment management (Linkov, Satterstrom, Seager, et al. 2006). We also discussed the relationship of MCDA, risk assessment, and adaptive management (Linkov, Satterstrom, Kiker, Batchelor, et al. 2006; Linkov, Satterstrom, Kiker, Bridges, et al. 2006). The application of different MCDA tools to the 2 sediment management case studies reported in this paper shows similar prioritizations of available sediment management alternatives by different tools, reinforcing the conclusions of our previous work about the usefulness of MCDA tools for sediment management and similar environmental problems.

MULTICRITERIA DECISION ANALYSIS METHODS

Environmental managers must decide what they wish to achieve through environmental management and how much they are willing to pay to achieve it. Those affected and involved in the decision making must also decide what they care about, how they prioritize those concerns, and how much they are willing to pay to achieve their objectives. Controversy arises when stakeholders differ in their objectives or priorities. There are many alternatives for the management of contaminated sediments, and there are important trade offs among ecological, economic, technical, and societal objectives. As an example of a trade off, achieving significant benefits and minimizing cost are 2 conflicting objectives. As a consequence, a given alternative may not take clear precedence over other alternatives with respect to every objective.

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This may present a dilemma to a decision maker trying to choose a single alternative.

The common purpose of MCDA methods is to evaluate and choose among alternatives based on multiple criteria using systematic analysis that overcomes the limitations of unstructured individual or group decision making (von Winterfeldt and Edwards 1986; Belton and Steward 2002). The following main categories of problems are considered on the basis of MCDA (Belton and Steward 2002):

- Sorting alternatives into classes/categories (e.g., "unacceptable," "possibly acceptable," "definitely acceptable," and so on);
- Screening alternatives—a process of eliminating those alternatives that do not appear to warrant further attention, that is, selecting a smaller set of alternatives that (very likely) contains the "best"/trade-off alternative;
- Ranking alternatives (from "best" to "worst" according to a chosen algorithm);
- Selecting the "best alternative" from a given set of alternatives; and
- Designing (searching, identifying, creating) a new action/alternative to meet goals.

Some other categories of problems, such as description/learning problematique (analysis of actions to gain greater understanding of what may or may not be achievable) and portfolio problematique (choice of a subset of alternatives, taking account not only of individual characteristics of each alternative but also of their positive and negative interrelations), may also be considered with the use of MCDA approaches.

Two key schools within the MCDA methodologies are considered in this paper. Each is based on the specific approaches to multiple criteria analysis and methods used: Value function–based methods and outranking methods.

Approaches that use value functions form the so-called MAVT methods. Multiattribute utility theory (MAUT) methods are also often used. While the methods are not always seen as fundamentally different (von Winterfeldt and Edwards, 1986), they are typically differentiated on the basis of certainty. A value function describes a person's preference regarding different levels of an attribute under certainty, whereas utility theory extends the method to use probabilities and expectations to deal with uncertainty (von Winterfeldt and Edwards 1986; Belton and Steward 2002). However, in many cases, when analyzing applied MCDA problems, authors do not distinguish MAVT and MAUT, indicating simply the implementation of MAVT/MAUT methods.

The objective of MAVT is to model and represent the decision maker's preferential system into a value function $V(\boldsymbol{a})$,

$$V(a) = F(V_1(a_1), ..., V_m(a_m)) \tag{1}$$

where alternative $\boldsymbol{a}$ is presented as a vector of the evaluation criteria $\boldsymbol{a} = (a_1, \ldots, a_m)$, a_i is the assessment of alternative $\boldsymbol{a}$ according to criterion i, and $V_i(a_i)$ is the value score of the alternative reflecting its performance on criterion i. The goal of decision makers in this process is to identify the alternative $\boldsymbol{a}$ that maximizes the overall value of $V(\boldsymbol{a})$. The most widely used form of function $F(\ )$ is an additive model:

$$V(a) = w_1 V_1(a_1) + ... + w_m V_m(a_m) \tag{2}$$

$$w_i \rangle 0, \sum w_1 = 1 \tag{3}$$

where w_i, $i = 1, \ldots, n$, are the weights reflecting the relative importance of criteria or corresponding scaling factors (von Winterfeldt and Edwards 1986; Belton and Steward 2002). It should be stressed, however, that for a justified implementation of the additive model (Eqn. 2), some requirements/axioms of MAVT should be held, especially the preferential independence requirements (von Winterfeldt and Edwards 1986; Belton and Steward 2002). MAVT relies on the assumption that the decision maker is rational (e.g., preferring more utility to less utility), that the decision maker has perfect knowledge, and that the decision maker is consistent in his judgments. Because poor scores on some criteria can be compensated for by high scores on other criteria, MAVT is part of a group of MCDA techniques known as compensatory methods.

Various sophisticated methods for defining partial value functions $V_i(x)$ and assessing weights w_i have been developed both for quantitative and qualitative criteria. One of the most popular and simplest versions of MAVT is the simple multiattribute rating technique (SMART; Figueira et al. 2005); at present, several versions of SMART are used (von Winterfeldt and Edwards 1986; Edwards and Barron 1994).

Outranking approaches imply forming an ordered relation of a given set of alternatives. Outranking methods are based on a pairwise comparison of alternatives for each criterion under consideration with subsequent integration of obtained preferences according to a chosen algorithm. Among outranking approaches, the ELECTRE family of methods developed by Roy (1996) and the PROMETHEE method developed by Brans and Vincke (Brans 1985) are the most used.

PROMETHEE is based on utilization of a performance matrix $\{z_i(\boldsymbol{a})\}$, where $z_i(\boldsymbol{a})$ is an evaluation of alternative $\boldsymbol{a}$ against criterion i, and a chosen preference function $f_i(x)$, $0 \leq f_i(x) \leq 1$, with specified indifference and preference thresholds. It determines the intensity of preference for alternative $\boldsymbol{a}$ over alternative $\boldsymbol{b}$, $P_i(\boldsymbol{a}, \boldsymbol{b}) = f_i(z_i(\boldsymbol{a}) - z_i(\boldsymbol{b}))$, and the preference index, $P(\boldsymbol{a}, \boldsymbol{b})$,

$$P(a, b) = \sum w_i P_i(a, b) \tag{4}$$

where weights w_i reflect the relative importance of criteria and meet the requirements of Equation 3. According to the features of preference functions $f_i(x)$, if $P_i(\boldsymbol{a}, \boldsymbol{b}) > 0$, then $P_i(\boldsymbol{b}, \boldsymbol{a}) = 0$. Preference indices are used for determination of positive outranking flow $Q^+(\boldsymbol{a})$:

$$Q^+(a) = \sum_b P(a, b) \tag{5}$$

and negative outranking flow $Q^-(\boldsymbol{a})$:

$$Q^-(a) = \sum_b P(b, a) \tag{6}$$

summed over all alternatives $\boldsymbol{b} \neq \boldsymbol{a}$.

According to the PROMETHEE 1 method, $\boldsymbol{a}$ outranks $\boldsymbol{b}$ if $Q^+(\boldsymbol{a}) \geq Q^+(\boldsymbol{b})$ and $Q^-(\boldsymbol{a}) \leq Q^-(\boldsymbol{b})$, $\boldsymbol{a}$ is indifferent to $\boldsymbol{b}$ if $Q^+(\boldsymbol{a}) = Q^+(\boldsymbol{b})$ and $Q^-(\boldsymbol{a}) = Q^-(\boldsymbol{b})$, $\boldsymbol{a}$ and $\boldsymbol{b}$ are incomparable if $Q^+(\boldsymbol{a}) > Q^+(\boldsymbol{b})$ and $Q^-(\boldsymbol{b}) < Q^-(\boldsymbol{a})$ or $Q^+(\boldsymbol{b}) > Q^+(\boldsymbol{a})$ and $Q^-(\boldsymbol{a}) < Q^-(\boldsymbol{b})$. Thus, PROMETHEE 1, like some other outranking methods, does not presuppose that a single best alternative can be identified since some alternatives may be incomparable. The PROMETHEE 2 method is based on the net flow criteria $Q(\boldsymbol{a})$:

$$Q(a) = Q^+(a) - Q^-(a) \tag{7}$$

and it may be used for a complete ranking of alternatives (and alternative $\boldsymbol{a}$ outranks $\boldsymbol{b}$ if $Q(\boldsymbol{a}) > Q(\boldsymbol{b})$).

Table 1. Alternatives for the Cocheco River case study (Rogers et al. 2004)

Technology	Process and hypothesis
Wetland restoration	Surrounding contaminated sediment core with clean material in new wetland cell may restore hydrologic function and ecological habitat to areas diked and/or drained
Cement manufacture	Blending with conventional raw materials and firing in rotary kiln for manufacture of cement may destroy organic contamination; metals may be bound on hydration of Portland cement in normal construction applications
Upland brownfield disposal cell	Dewatering, compacting, and capping on site may prevent dispersion of contaminants to the environment and allow construction of recreation space on top of cell
Cement stabilization in flowable fill	Blending with pozzolanic material such as cement, fly ash, or blast furnace slag may bind contaminants on hydration in normal structural applications such as trench backfilling or soil strengthening

PROMETHEE, like other outranking methods, is considered an attractive and transparent method, although both positive and negative flows depend on the complete set of alternatives under consideration (Brans and Vincke 1985; Belton and Steward 2002). However, a drawback of outranking is that "indifference" and "preference" thresholds—though often based on expert knowledge—are essentially arbitrary, and the relationship representing which alternatives outrank which depends on selection of those thresholds. One way to analyze the robustness and check consistency between thresholds is to manipulate the thresholds.

Outranking techniques allow inferior performance on some criteria to be compensated by superior performance on others (Roy 1996; Belton and Steward 2002). They do not necessarily, however, take into account the magnitude of relative underperformance in a criterion versus the magnitude of overperformance in another criterion. Therefore, outranking models are known as "partially compensatory."

The AHP, developed by Saaty (1980), presents an integration of the additive model (Eqn. 2) with a distinctive determination of the decision matrix, $V_{i,\boldsymbol{a}}$, and criteria weights, w_i, $i = 1, \ldots, n$. Within AHP, a systematic pairwise comparison of alternatives with respect to each criterion is used based on a special ratio scale: For a given criterion, alternative i is preferred to alternative j with the strength of preference given by $a_{ij} = s$, $1 \leq s \leq 9$; correspondingly, $a_{ji} = 1/s$. Then, the same procedure is implemented for $n(n-1)/2$ pairwise comparisons in the same scale for n criteria. The obtained matrices are processed (by extracting the eigenvector corresponding to the maximum eigenvalue of the pairwise comparison matrix) (Saaty 1980; Belton and Steward 2002) and yield the values $V_{i,\boldsymbol{a}}$ and weights w_i for subsequent use with the model, when preferences are aggregated across different criteria according to Equation 2.

AHP may thus be considered an MAVT approach with a specific elicited value function (scoring) and criteria weights (weighting). However, taking into account different assumptions and approaches, proponents of AHP insist that it is not a value function method (Belton and Steward 2002). Additionally, AHP 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 MAVT.

Despite long-standing discussions on the correctness of AHP for analyzing and ranking alternatives (including specific issues such as the "rank reversal problem"; Dyer 1990), its transparency and relatively simple pairwise judgments make it a popular decision analysis method.

COCHECO RIVER AND NEW YORK/NEW JERSEY HARBOR CASE STUDIES

The 2 case studies are representative of sediment management challenges faced by the US Army Corps of Engineers (USACE) and other agencies.

The Cocheco River, the 1st case study, is located in southeastern New Hampshire (USA) and flows toward the Gulf of Maine and the Atlantic Ocean. A section of the river,

Table 2. Performance table for the Cocheco River case study (Rogers et al. 2004)

Alternatives/criteria	Cost ($/cubic yard)	Environmental quality	Ecological habitat (acres)	Human habitat (acres)
Wetlands restoration	$75	High	10 addn.	No change
Cement manufacture	$30	High	No change[a]	No change
Upland disposal cell	$40	Medium	No change	4 addn.
Flowable fill	$55	Medium	No change	No change

[a] No change = 0.

Table 3. Performance table for the New York/New Jersey (USA) case study (Kiker et al. 2005)

Criteria/alternatives	**Confined aquatic disposal**	**Island confined disposal facilities (CDF)**	**Nearshore CDF**	**Upland CDF**	**Landfill**	**No action**	**Cement lock technology**	**Manufactured soil technology**
Magnitude of ecological hazard quotient	680	2,100	900	900	0	5,200	0	8.7
Complete ecological exposure pathways	23	38	38	38	0	41	14	18
Complete human health exposure pathways	18	24	24	24	21	12	25	22
Magnitude of maximum cancer risk (non–barge worker)	0.03	0.09	0.04	0.04	0.3	0.2	0.02	1
Estimated concentration of contaminant of concern in fish/risk-based concentration	28	92	38	38	0	220	0	0
Cost ($/cubic yard)	5	25	15	20	70	2	75	60
Ratio of impacted area to facility capacity (acres/million cubic yards)	4,400	980	6,500	6,500	0	0	0	750

Table 4. Criteria weights (%) for different scenarios in the Cocheco River case study (Rogers et al. 2004)

Scenario/criterion	Cost	Environmental quality	Ecological habitat	Human habitat
Eco-environmental	10	30	40	20
Human health	10	30	30	30
Commercial	30	30	10	30
Balanced	25	25	25	25

from below the dam in the center of the city of Dover (DE, USA) to the Cocheco River's confluence with the Piscataqua River, was proposed for dredging. Plans to dredge have been in the works for a number of years (since ~1996). There are many motivations for the dredging, including the economic redevelopment of Dover and the overriding goal of maintaining a navigable channel for federal navigation. Because it is a navigable waterway, USACE has been helping the city of Dover coordinate the process and will be performing the dredging. There has been much debate over the need to dredge and remove sediment from the bottom of the Cocheco River. Approximately 34,000–46,000 m of sediment, some of which are contaminated with polyaromatic hydrocarbons and heavy metals, are planned for removal. The decision regarding what to do with the contaminated sediment is not an easy one. Regulatory constraints required secure disposal of contaminated materials (i.e., prohibiting ocean dumping). Other commonly used options (contained aquatic disposal, landfill) were not found to be useful for the site. After extensive negotiations, cement manufacture, flowable fill, wetlands restoration, and an upland disposal cell were identified as feasible alternatives for consideration (Rogers et al. 2004; Table 1).

In the 2nd case study, contaminated sediment management issues within the greater New York/New Jersey (NY/NJ) Harbor area are considered (Wakeman and Themelis 2001; Driscoll et al. 2002). Several million cubic meters of sediment must be dredged each year to maintain navigation channels for harbor access. Because of long-term human use of the harbor area, significant contaminant concentrations have been recorded in certain areas (Table 3). Additional challenges in sediment management have been created by the limitation of ocean disposal to only clean sediments and plans for deepening existing channels to allow increased access for large transport vessels. New and innovative sediment management options, along with their associated risk and decision analyses, are required for contaminated sediments within the NY/NJ Harbor area and need to be systematically explored for cost-efficient risk reduction. A detailed description of the possible alternatives for NY/NJ case study is presented in Driscoll (2002; Table 3).

In both case studies, stakeholders in the decision-making process have a wide array of concerns, some overlapping and others exclusive, about the management of contaminated sediments (Rogers et al. 2004; Kiker et al. 2005). MCDA methods and tools provide a sound approach to sediment management that integrates economic and technical considerations (such as cost, human health risks, and environmental risks) with social factors (public acceptance, environmental justice, and others).

METHODOLOGY

To test the sensitivity of the "optimal" management alternative to the specific MCDA method used, this investigation employs all 3 methods discussed previously—MAVT (SMART approach), outranking (PROMETHEE), and AHP—and compares the resulting selection of a sediment management alternative for the 2 case studies.

The starting points for the analysis presented in this study were the performance matrices developed for the Cocheco and NY/NJ case studies. The performance matrix for the Cocheco case study (Table 2) presents an evaluation of 4 alternative policies using 4 criteria: Cost, environmental quality, and impact on ecological and human health habitats (Rogers et al. 2004). The measures associated with the criteria are cost per cubic yard, environmental quality, change of ecological habitat, and change of human habitat, in acres (the possible decrease or increase of ecological or human habitat

Table 5. Criteria weights (%) for different scenarios in the New York/New Jersey (USA) case study (Kiker et al. 2005)

Criterion/scenario	USEPA experts[a]	USACE experts[b]	SRA Workshop participants[c]
Impacted area/capacity	7.37	12.46	10.77
Magnitude of ecological hazard quotient	20.29	14.72	16.58
Ecological pathways	15.36	12.40	15.87
Human pathways	12.81	14.79	12.63
Magnitude of cancer risk	18.86	14.13	18.48
Ratio of fish contaminant of concern/risk level	15.33	11.82	13.00
Cost	9.97	19.66	12.67

[a] USEPA = US Environmental Protection Agency.

[b] USACE = US Army Corps of Engineers.

[c] SRA = Society of Risk Analysis.

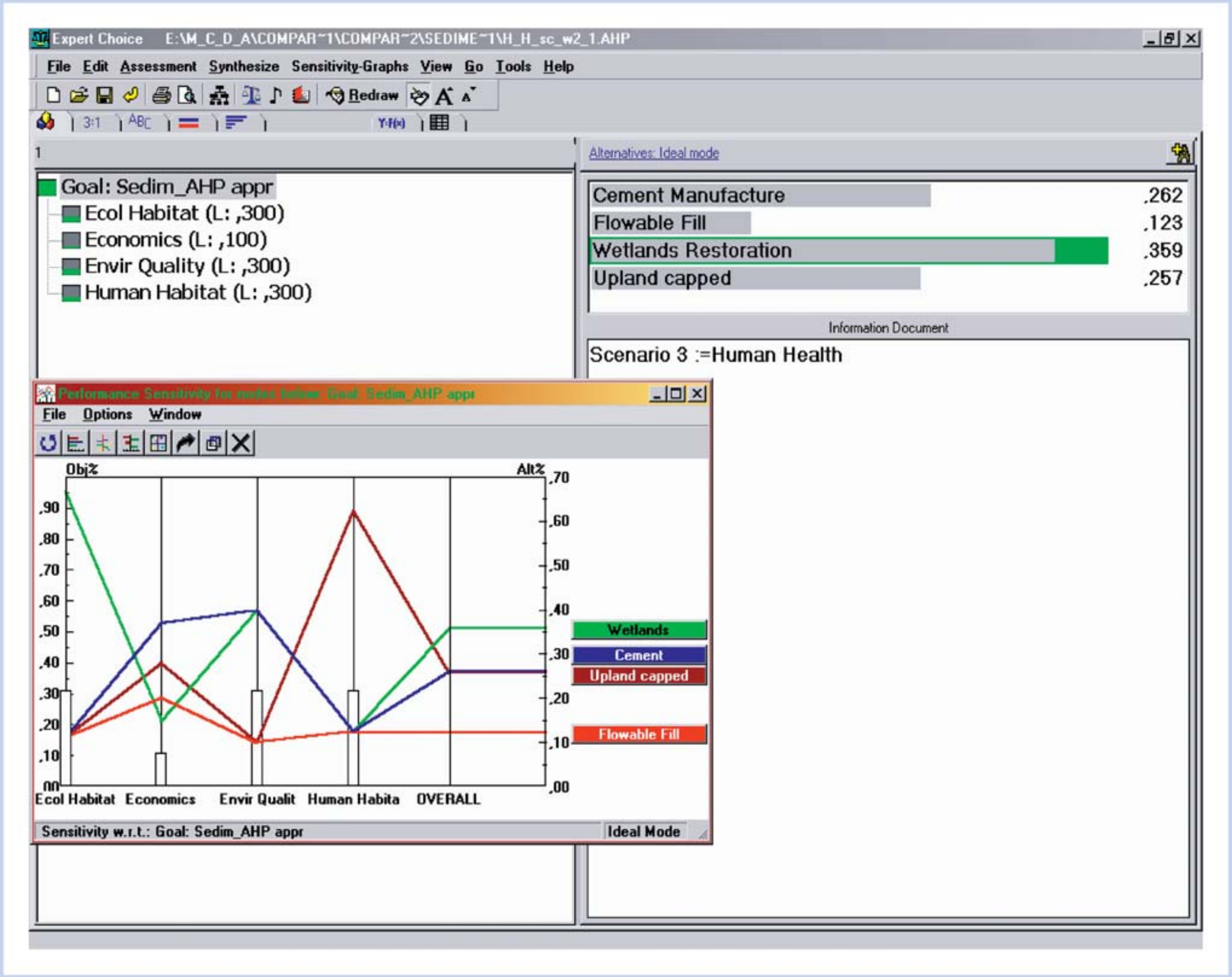
Table 6. Ranking alternatives for the Cocheco River case study using different multicriteria decision analysis methods (2 criteria weighting scenarios are considered: eco-environmentalists/public health)[a]

Software and method	Alternatives			
	Wetlands restoration	Cement manufacture	Upland capped	Flowable fill
ExpertChoice, AHP[a]	1/1	2/2	3/3	4/4
DecisionLab, PROMETHEE	1/1	2/2	3/3	4/4
CritDecPlus, MAVT[b]	1/1	3/3	2/2	4/4

[a] AHP = analytical hierarchy process.
[b] MAVT = multiattribute value theory.

area after implementation of corresponding measures). One of these measures, environmental quality, is qualitative and uses a 3-level scale of low, medium, and high. Other measures are quantitative.

The performance table for the NY/NJ case study (Table 3) presents an evaluation of 8 alternative policies using 7 quantitative criteria (Kiker et al. 2007): Ecological risk criteria (ecological hazard quotient and complete ecological exposure pathways), human health risk criteria (complete human health exposure pathways, maximum cancer probability in non–barge workers, and estimated chemical of concern concentration in fish divided to risk-based concentration), economic criterion (cost), and public acceptability criterion (ratio of impacted area to facility capacity). The criteria present different quantitative measures (relative numbers for hazard quotient and chemical of concern; ecological/human exposure pathways presented with whole numbers; and economic and ecological values, expressed in dollars and acres per cubic yard) and different scales with



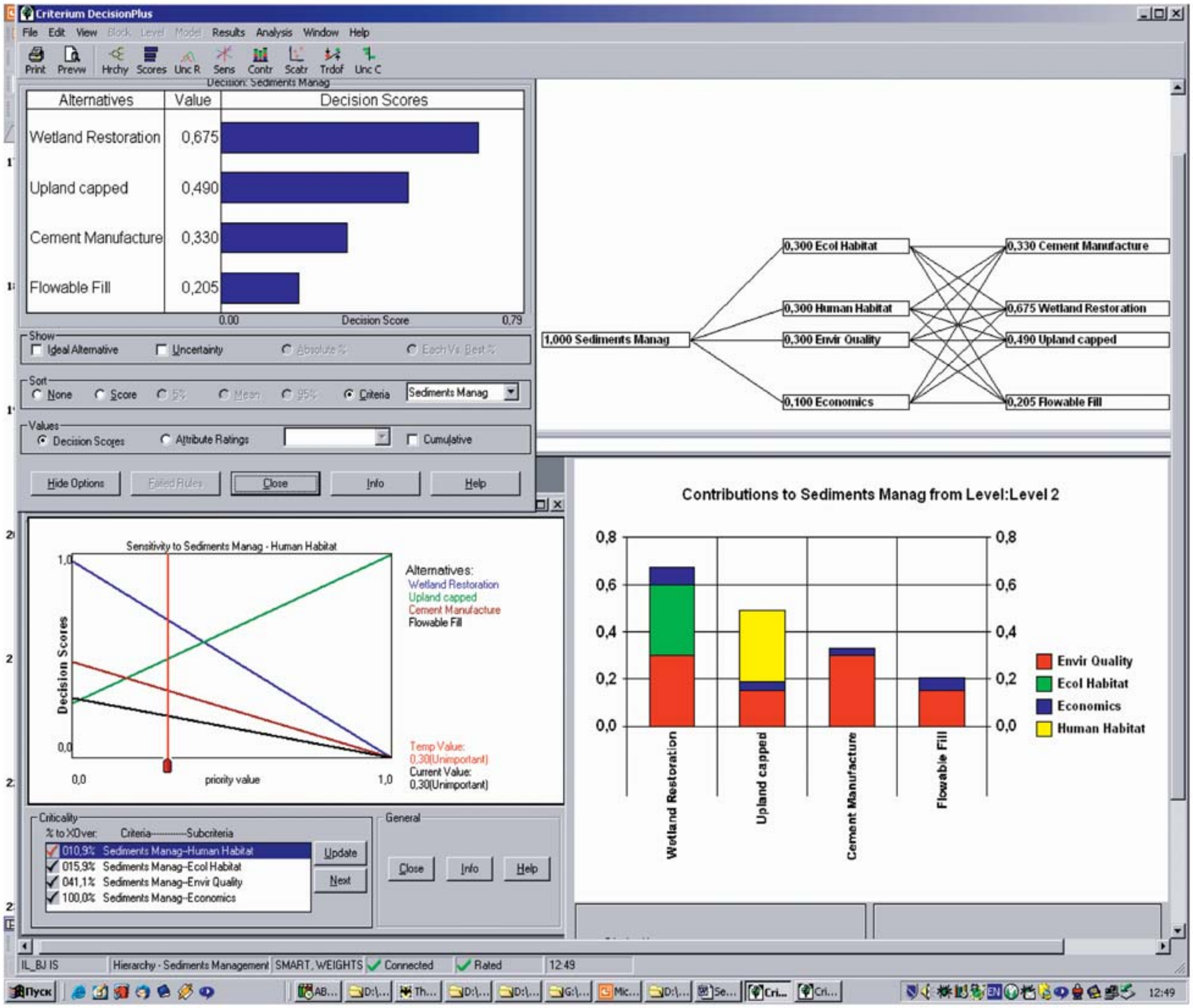
Goal: Sedim_AHP appr
- Ecol Habitat (L: ,300)
- Economics (L: ,100)
- Envir Quality (L: ,300)
- Human Habitat (L: ,300)

Cement Manufacture	,262
Flowable Fill	,123
Wetlands Restoration	,359
Upland capped	,257

Scenario 3 :=Human Health

Sensitivity w.r.t.: Goal: Sedim_AHP appr

Figure 1. Cocheco River case study: Alternative ranking and sensitivity analysis, AHP/Expert Choice (human health scenario).



Decision: Sediments Manag

Alternatives	Value	Decision Scores
Wetland Restoration	0,675	
Upland capped	0,490	
Cement Manufacture	0,330	
Flowable Fill	0,205	

Show: ☐ Ideal Alternative ☐ Uncertainty ○ Absolute % ○ Each Vs. Best %

Sort: ○ None ○ Score ○ 5% ○ Mean ○ 95% ● Criteria Sediments Manag

Values: ● Decision Scores ○ Attribute Ratings ☐ Cumulative

1,000 Sediments Manag
0,300 Ecol Habitat
0,300 Human Habitat
0,300 Envir Quality
0,100 Economics
0,330 Cement Manufacture
0,675 Wetland Restoration
0,490 Upland capped
0,205 Flowable Fill

Temp Value: 0,30(Unimportant)
Current Value: 0,30(Unimportant)

Criticality

% to XOver:	Criteria---------Subcriteria
✓ 010,9%	Sediments Manag--Human Habitat
✓ 015,9%	Sediments Manag--Ecol Habitat
✓ 041,1%	Sediments Manag--Envir Quality
✓ 100,0%	Sediments Manag--Economics

IL_BJ IS | Hierarchy - Sediments Management | SMART, WEIGHTS | ✓ Connected | ✓ Rated | 12:49

Figure 2. Cocheco River case study: Alternative ranking and sensitivity analysis using MAVT/CDplus for the human health scenario.

considerable variability (from 0 to 1 for risk, and from 0 up to 5,200 for hazard quotient).

Performance Tables 2 and 3 were transformed to fit input data formats for different software packages:

1. Decision Lab, which employs the PROMETHEE method;
2. Expert Choice, which uses the AHP method; and
3. Criterium Decision Plus, which implements MAVT (using the SMART approach)

All the indicated packages possess wide performance capabilities, including sensitivity analysis, presentation of various output tables, and graphic user interfaces.

Experts and stakeholders were involved in structuring the MCDA problems mentioned previously for the Cocheco River and NY/NJ case studies, developing the performance tables, and criteria weighting (Rogers et al. 2004; Kiker et al. 2007). Four stakeholder group preference scenarios and the weights that might be elicited therefrom were originally elaborated within the Cocheco River case study (Rogers et al. 2004; Table 4). Two of the scenarios (Eco-Environmental and Human Health) are considered in this work. Three scenarios for weights were proposed within the NY/NJ case study (Kiker et al. 2007): 10–20 (non-NY) experts from USACE, USEPA, and participants of a Society of Risk Analysis workshop (Linkov, Satterstrom, Seager, et al. 2006) were given a swing weight survey to calculate criteria weights. Average criteria weights for each group are presented in Table 5, and 1 of them (in which experts involved in the weighting process are envisioned to be affiliated with the USEPA) is considered in the present investigation (Table 5).

For the MCDA analysis of the Cocheco River case study, the software package Decision Lab was originally used (Rogers et al. 2004), and analysis of the NY/NJ case study was originally based on the Criterium Decision Plus package (Kiker et al. 2007). Implementation of other software packages for cross analysis of indicated case studies was based on performance tables (Tables 2 and 3) and corresponding criteria weights (Tables 4 and 5).

The historical data and expert comments were taken into account for comparison of ranking orders for the case studies and software packages. Linear value functions within MAVT were used for all scenarios, and linear (for NY/NJ case study) and U-shape (for Cocheco River case study) preference functions within PROMETHEE were used.

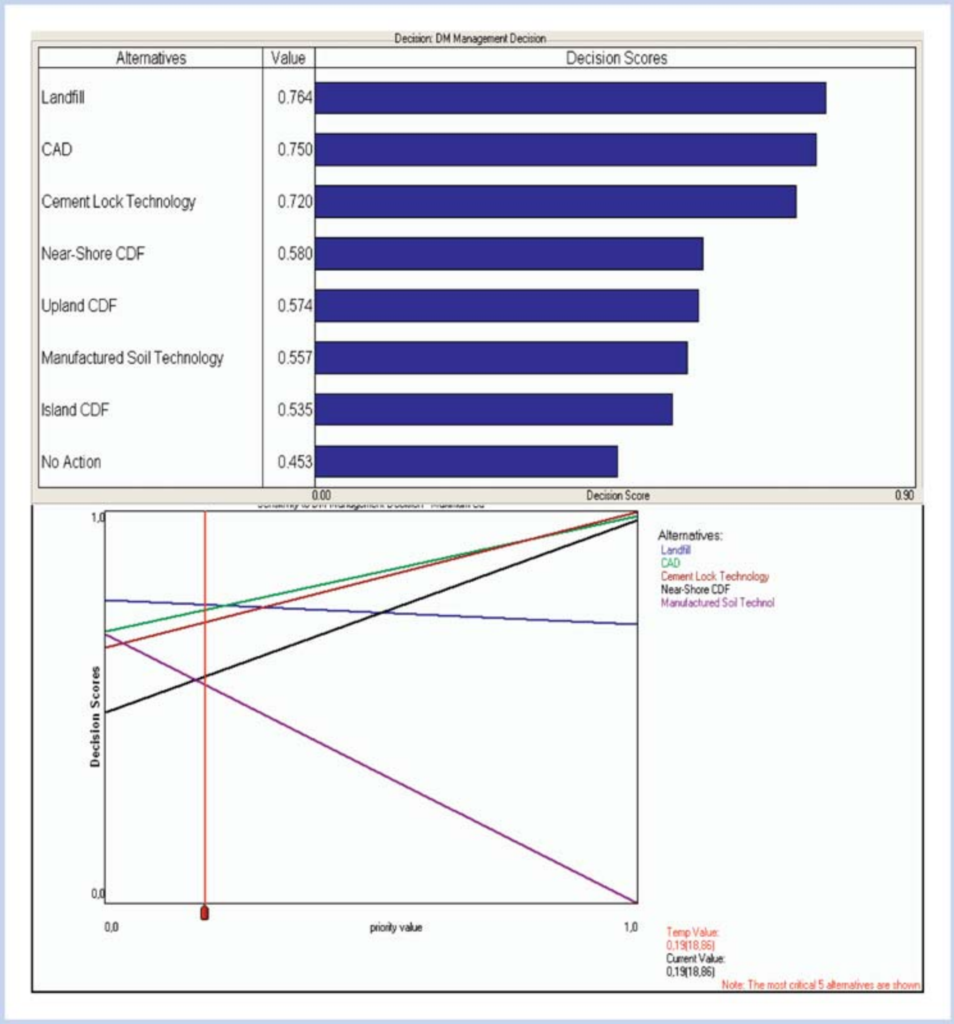


Figure 3. NY/NJ (USA) case study: alternative ranking and sensitivity analysis using MAVT/CDplus.

RESULTS

We discuss here only the ranking order of the alternatives for the 2 case studies under consideration.

Table 6 presents an alternative ranking for the Cocheco River case study using different software packages. The performance matrix (Table 2) presented previously was used for both software packages. The MCDA software packages used in this work predict that flowable fill is the least attractive alternative for both stakeholder preference scenarios. Wetland restoration was ranked as the most attractive option by all methods for the 2 indicated groups of stakeholders. Cement manufacture and upland capped ranked 2 or 3, depending on the method used (Table 6).

According to sensitivity analysis, using the PROMETHEE and human health scenario, increasing the weight for the human habitat criterion from 30% (Table 4) to 35% changes

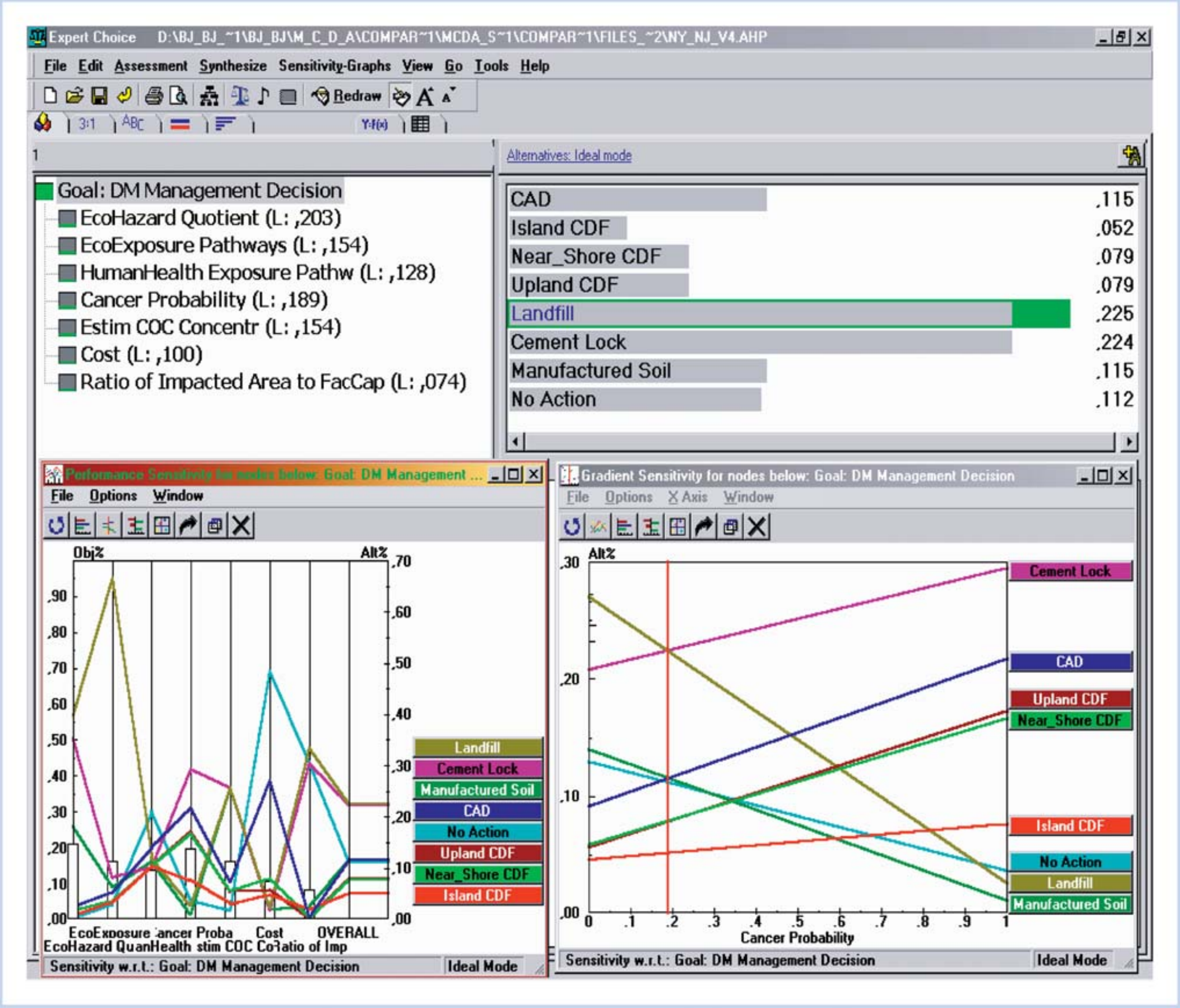
Table 7. Ranking alternatives for New York/New Jersey (USA) case study sites using different multicriteria decision analysis methods

Software and method	Alternatives							
	CAD	Island CDF[a]	Nearshore CDF	Upland CDF	Landfill	Cement lock	Manufactured soil	No action
ExpertChoice, AHP[b]	3–4	8	6–7	6–7	1–2	2–1	3–4	5
DecisionLab, PROMETHEE 1,2	2	8	5	6	3	1	4	7
CritDecPlus, MAVT[c]	2	7	4	5	1	3	6	8

[a] CDF = combined disposal facilities.

[b] AHP = analytical hierarchy process.

[c] MAVT = multiattribute value theory.


Expert Choice D:\BJ_BJ_~1\BJ_BJ\M_C_D_A\COMPAR~1\MCDA_S~1\COMPAR~1\FILES_~2\NY_NJ_V4.AHP

Goal: DM Management Decision
- EcoHazard Quotient (L: ,203)
- EcoExposure Pathways (L: ,154)
- HumanHealth Exposure Pathw (L: ,128)
- Cancer Probability (L: ,189)
- Estim COC Concentr (L: ,154)
- Cost (L: ,100)
- Ratio of Impacted Area to FacCap (L: ,074)

Alternatives: Ideal mode

CAD	,115
Island CDF	,052
Near_Shore CDF	,079
Upland CDF	,079
Landfill	,225
Cement Lock	,224
Manufactured Soil	,115
No Action	,112

Figure 4. NY/NJ (USA) case study: alternative ranking and sensitivity analysis, AHP/Expert Choice.

the ranking orders of the cement manufacture and upland capped alternatives, whereas doubling the weight of the cost criterion (from 10% to 20%) changes the ranks of wetland restoration and cement manufacture.

Figure 1 (implementation of AHP for the human health scenario) shows the chosen criteria and weights for the Cocheco River case study (upper left corner), overall scores for alternatives (upper right corner), and performance sensitivity analysis (panel in the center). Using the AHP method for the human health scenario of this case study demonstrates (Figure 1) that the difference between the cement manufacture and upland capped alternatives is negligible.

Figure 2 (implementation of MAVT for the human health scenario) shows the value tree for the Cocheco River case study (upper right corner), overall scores for alternatives (upper left corner), contribution of criteria to overall score for each alternative (bottom right corner), and gradient sensitivity analysis (bottom left corner). In contrast to alternative ranking on the basis of AHP (Figure 1), the ranking order for alternatives on the basis of MAVT (Figure 2) is not subject to effects such as rank reversal and may be considered relatively robust.

For the NY/NJ case study, cement lock, landfill, and CAD were ranked as top choices by all 3 software tools (Table 7). That CAD ranks 3 or 4 within the AHP method (Table 7) is a result of uncertainty influences when transforming data from the performance table (Table 4) into the AHP scale. Figures 3 (upper panel) and 4 (panel in upper right corner) demonstrate the differences in ranking order for alternatives obtained on the basis of MAVT (Figure 3) and AHP (Figure 4) methods. In both cases the alternative ranking is very sensitive to small changes of criteria weights (see bottom panels in Figures 3 and 4). Differences between the scores for landfill and CAD, as well as between nearshore CDF and upland CDF, are negligibly small according to MAVT (Figure 3). Differences between landfill and cement lock, as well as between CAD and manufactured soil, are also negligibly small according to AHP (Figure 4).

In addition, a rank reversal effect for AHP was observed when decreasing the number of alternatives from 8 to 5 (e.g., the rank ordering of CAD and manufactured soil changed).

Thus, despite a relative increase in discrepancies of rank ordering for the NY/NJ case study (Table 7, as compared to the Cocheco River case study, Table 6), the results support the finding that 3 alternatives indicated previously can be considered for further analysis as the most justified on the basis of MCDA.

DISCUSSION

Since a number of different MCDA methods are available, it may be difficult to select 1 or the "most suitable" method for a given situation. In addition, any ranking of available management alternatives that is based on the application of just 1 of a multitude of the available MCDA tools may be questioned. We showed, for example, the variability of sediment management alternative rankings in the output of different MCDA methods for 2 case studies.

Our analysis shows that even though each MCDA method and its associated tools may use a unique theoretical background and calculation algorithms, a comparative analysis of results on the basis of different MCDA methods (MAVT, outranking, and AHP) demonstrates similar ranking orders for alternatives within the 2 case studies considered.

For example, the Cocheco River case study shows that flowable fill is clearly the least appropriate alternative and can be safely removed from consideration. Three other alternatives may be ranked in the following order: Wetlands restoration followed by cement manufacture or upland capped. Although ranking alternatives on the basis of MAVT for this case study may be considered relatively robust, implementation of other methods (AHP, PROMETHEE) demonstrates nonrobustness of ranking order for the 2nd and the 3rd alternatives.

For the NY/NJ case study, the top 3 alternatives (landfill, cement lock, and CAD) clearly outperform the remaining 5, and the ranking order is sensitive to the methods implemented and to relatively small change of weights. For this case study, all 3 MCDA methods demonstrate nonrobustness of ranking order for alternatives under consideration. However, all the methods consistently rank the 3 indicated alternatives over the others.

Certainly, if 2 different groups of experts analyze a given task using the same method (e.g., outranking), the resulting alternative rankings may not completely coincide until the results given here (e.g., when groups suggest different criteria weights and/or ranking is sensitive to the preference functions or indifference/preference thresholds). And if 2 expert groups make their judgments with the aid of 2 facilitators who use different methods (e.g., MAVT and outranking), the ranking order may not be the same even if these groups nearly coincide. In fact, if within a MAVT approach the criteria weights were elaborated as swing weights, that is, as scaling factors (which relate scores on 1 criterion to scores on other criteria), then these weights may differ from weights elicited within an outranking approach based on ranking or rating methods. In addition, implementation of value functions $V_i(x)$ and intensity of preference functions $P_i(\boldsymbol{a}, \boldsymbol{b})$ developed by expert groups may also increase differences in ranking order for alternatives, which are based on the overall value function $V(\boldsymbol{a})$ and outranking flows $Q^+(\boldsymbol{a})$ and $Q^-(\boldsymbol{a})$.

Specific differences in ranking order also occur if 1 of the expert groups makes its judgments working with a facilitator within AHP while another group does the same within MAVT or outranking. Moreover, in this situation there are no well-defined and unique rules for transforming both quantitative and qualitative criteria performances from a set of data developed under MAVT/outranking into the AHP scale. Although a pairwise comparison of alternatives against a quantitative criterion is effective, an automatic transformation of pairwise ratios based on numerical values of criteria (see, e.g., Table 3) as well as from interval (0, 1,000) into the standard AHP value scale ($1 \leq s \leq 9$ and $1/9 \leq 1/s \leq 1$) may differ from corresponding judgments made by experts using the AHP method.

Although the ranking order of alternatives may change when using different MCDA methods, a multiple platform analysis (i.e., analysis of the same problem using several MCDA methods simultaneously) may play an effective role in the interactive and iterative process of problem understanding and eliciting key parameters and functions of the methods being implemented. A multiple-platform approach is also valuable for subsequent decision making and can help managers think hard about a problem, develop a consistent set of preferences, and have confidence in their judgments. Also, although there is no such thing as a right answer within MCDA approaches (Belton and Steward 2002), decision makers need a justified method that can be verified using other approaches (cross validation in a broad sense).

Certainly, there are questions concerning realization of such a multiple platform analysis: Is such a multiple platform analysis, realized by analyst(s), "correct," or should it be carried out by nonoverlapping groups of experts and stakeholders? Can a multiple platform analysis give more then sensitivity/uncertainty analysis on the basis of 1 method?

This paper utilizes different MCDA packages to conduct analysis of the same problem. We found that sensitivity analysis of the alternative management action is difficult because of different software/method requirements. We are currently designing a decision support module (DSM) under the DOE DEcision Management and Evaluation Tool using Risk Assessment (DEMETRA) project. The DSM will be realized as a Java-based library of classes and templates implementing different decision analysis methods and tools. DSM will also provide the ability to compare and contrast decision actions recommended by several MCDA methods.

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REFERENCES

Belton V, Steward T. 2002. Multiple criteria decision analysis: An integrated approach. Dordrecht (NL): Kluwer Academic. 372 p.

Brans JP, Vincke P. 1985. A preference ranking organization method: The PROMETHEE method for multiple criteria decision-making. *Management Science* 31:647–656.

Dyer JS. 1990. Remarks on the analytic hierarchy process. *Management Science* 36:249–258.

Edwards W. 1971. Social utilities. *Engineering Economist, Summer Symposium Series* 6:119–129.

Edwards W, Barron FH. 1994. SMART and SMARTER: Improved simple methods for multiattribute utility measurement. *Organizational Behavior and Human Decision Process* 60:306–325.

Driscoll Kane SB, Wickwire WT, Cura JJ, Vorhees DJ, Butler C, Moore DM, Bridges T. 2002. A comparative screening-level ecological and human health risk assessment for dredged material management alternatives in New York/New Jersey Harbor. *Human and Ecological Risk Assessment* 8:603–626.

Figueira J, Greco S, Ehrgott M, editors. 2005. Multiple criteria decision analysis: State of the art surveys. New York (NY): Springer.

Kiker G, Bridges TS, Kim JB. 2007. Integrating comparative risk assessment with multi-criteria decision analysis to manage contaminated sediments: An example from New York/New Jersey Harbor. *Human and Ecological Risk Assessment* (forthcoming).

Kiker G, Bridges T, Linkov I, Varghese A, Seager T. 2005. Application of multi-criteria decision analysis in environmental decision-making. *Integr Environ Assess Manag* 1:1–14.

Linkov I, Sahay S, Seager TP, Kiker G, Bridges T. 2005. Multi-criteria decision analysis: A framework for managing contaminated sediments. In: Levner E, Linkov I, Proth JM, editors. Strategic management of marine ecosystems. Berlin (DE): Springer.

Linkov I, Satterstrom K, Kiker G, Batchelor CG, Bridges T. 2006. From comparative risk assessment to multi-criteria decision analysis and adaptive management: Recent developments and applications. *Environ Int* 32:1072–1093.

Linkov I, Satterstrom K, Kiker G, Bridges T, Benjamin S, Belluck D. 2006. From optimization to adaptation: Shifting paradigms in environmental management and their application to remedial decisions. *Integr Environ Assess Manag* 2:92–98.

Linkov I, Satterstrom K, Seager TP, Kiker G, Bridges T, Belluck D, Meyer A. 2006. Multi-criteria decision analysis: Comprehensive decision analysis tool for risk management of contaminated sediments. *Risk Anal* 26:61–78.

Rogers SH, Seager TP, Gardner KH. 2004. Combining expert judgment and stakeholder values with PROMETHEE: A case study in contaminated sediments management. In: Linkov I, Ramadan AB, editors. Comparative risk assessment and environmental decision making. Boston (MA): Kluwer Academic. p 305–322.

Roy B. 1996. Multicriteria methodology for decision aiding. Dordrecht (NL): Kluwer Academic.

Saaty TL. 1980. The analytic hierarchy process. New York (NY): McGraw-Hill.

Salminen P, Hokkanen J, Lahdelma R. 1998. Comparing multicriteria methods in the context of environmental problems. *European Journal of Operational Research* 104:485–496.

Tecle A. 1992. Selecting a multicriteria decision making technique for watershed resource management. *Water Res Bull* 28:129–140.

von Winterfeldt D, Edwards W. 1986. Decision analysis and behavioral research. Cambridge (UK): Cambridge University Press. 604 p.

[USACE] US Army Corps of Engineers. 1999. Dredged Material Management Plan (DMMP) for the Port of New York and New Jersey. http://www.nan.usace.army.mil/business/prjlinks/dmmp/index.htm. Accessed 10 March 2006.

Wakeman TH, Themelis NJ. 2001. A basin-wide approach to dredged material in New York/New Jersey Harbor. *J Hazard Mater* 85:1–13.