RESTORING AQUATIC ECOSYSTEMS ON THE BASIS OF THE GMAA DSS

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ABSTRACT

The Generic Multi-Attribute Analysis System is a decision support system based on an additive multi-attribute utility model that is intended to allay many of the operational difficulties involved in the multicriteria decision-making process. In this paper we illustrate the application of this decision support system to the restoration of aquatic ecosystems in two contamination scenarios simultaneously taking into account several conflicting objectives, like environmental, social and economic impacts. In the first scenario, the contamination is by radionuclides produced, for instance, by a nuclear plant accident / disaster, like the Chernobyl or, more recently, Fukushima disasters. In the second scenario, intervention strategies are selected to combat eutrophication and the sharp decline in the bird population in Ringkøbing Fjord (Denmark).

Keywords: decision support system, multi-attribute utility theory, restoration of aquatic ecosystems

1. INTRODUCTION

Most of the real decision-making problems that we face nowadays are complex in the sense that they are usually plagued with uncertainty, and several conflicting objectives have to be taken into account simultaneously.

Decision support systems (DSS) play a key role in these situations helping decision-makers (DMs) to structure and gain a better understanding of the problem and finally make a decision.

DSS are becoming increasingly popular in environmental management (Stam, Salewizc and Aronson 1998; Tecle, Shrestha and Duckstein 1998; Ito, Xu, Jinno, Hojiri and Kawamura 2001; Poch, Comas, Rodríguez-Roda, Sánchez-Marré and Cortés 2004).

There are umber of examples where multi-attribute utility theory (MAUT) has been used for environmental management problems can be found, e.g., in the field of forest management (Ananda and Herath 2009), natural resource management (Mendoza and Martins 2006)), different fields of water management (Joubert, Stewart, Eberhard 2003), river management (Reichert, Borsuk, Hostmann, Schweizer, Sporri, Tockner, and Truffer 2007; Corsair, Ruch, Zheng, Hobbs and Koonce 2009), landscape ecology (Geneletti 2005), evaluation of farming systems (Prato and Herath 2007), and site selection for hazardous waste management (Merkhofer, Conway and Anderson 1997).

In this paper we will illustrate the application of the generic multi-attribute analysis (GMAA) system to the restoration of aquatic ecosystems contaminated by radionuclides and to the selection of intervention strategies against eutrophication and the sharp decline in the bird population in Ringkøbing Fjord (Denmark).

We have divided the paper into a further three sections. Section 2 outlines the GMAA system and its main characteristics are introduced, and Sections 3 and 4 address the complex decision-making problems pointed out above.

2. THE GENERIC MULTI-ATTRIBUTE ANALYSIS DSS

The GMAA system is a PC-based DSS based on an additive multi-attribute utility model that is intended to allay many of the operational difficulties involved in the Decision Analysis (DA) cycle (Jiménez, Ríos Insua and Mateos 2003, 2006, Jiménez and Mateos 2011).

The GMAA system accounts for uncertainty about the alternative performances and for incomplete information about the DM's preferences, leading to classes of utility functions and weight intervals. This is less demanding for a single DM and also makes the system suitable for group decision support, where individual conflicting views in a group of DMs can be captured through imprecise answers.

An additive multi-attribute utility function is used to evaluate the alternatives. This is considered to be a valid approach in most practical situations for the reasons described in (Raiffa 1982; Sterwart 1996).

The GMAA provides several types of sensitivity analysis (SA). For instance, it computes the *potentially optimal alternatives* among the *non-dominated alternatives*.

Monte Carlo simulation techniques enable simultaneous weight changes and generate results that can be easily analyzed statistically to provide more insight into the multi-attribute model recommendations (Mateos, Jiménez and Ríos Insua 2006).

3. RESTORING AQUATIC ECOSYSTEMS CONTAMINATED BY RADIONUCLIDES

The restoration of radionuclide contaminated aquatic ecosystem has been studied in depth as a part of several

EU projects in which we have participated: *MOIRA* (1997-98), *COMETES* (1999-2001), *EVANET-HYDRA* (2001-04) and *EURANOS* (2004-08).

A synthetic, flexible and user-friendly computerized DSS, MOIRA, was implemented as a part of these projects. The MOIRA system included a multi-attribute analyses module for the global assessment of the effectiveness of the intervention strategies. This module was the origin of the GMAA system, which was finally built into the final versions of the MOIRA system.

The selection of intervention strategies was based on environmental models for predicting the migration of radionuclides through freshwater and coastal ecosystems and the effects of feasible countermeasures on contamination levels. Other social and economic criteria were also taken into account.

The MOIRA system was tested on several real scenarios contaminated as a consequence of the Chernobyl accident, like lake Øvre Heimdalsvatn (Jiménez et al., 2003), located in Oppland county (Norway); lake Kozhanovskoe (Ríos Insua, Mateos, Jiménez 2004), located in the region of Bryansk (Russia); and lake Svyatoye in Belarus (Ríos Insua, Gallego, Jiménez, Mateos 2006).

Specifically, lake Kozhanovskoe was heavily contaminated with ^{137}Cs after the Chernobyl accident in 1986. In 1998, it was classed as a radio-ecological reserve, and fishery was officially forbidden because of the high levels of fish contamination with ^{137}Cs. The population around the lake, which lay in the population evacuation zone, was evacuated, as the levels of contamination with ^{137}Cs were rather high (^{137}Cs fallout on the lake was about 600000 Bq/m^2). However, many residents continued to live in villages near the lake, and fish caught in lake Kozhanovskoe were a predominant source of food of for local residents even 10 years on from the Chernobyl accident.

An objective hierarchy was built for this decision-making problem, which intended to provide the grounds for the description and evaluation of the hypothetical restoration alternatives for the scenario in question, see Figure 1.

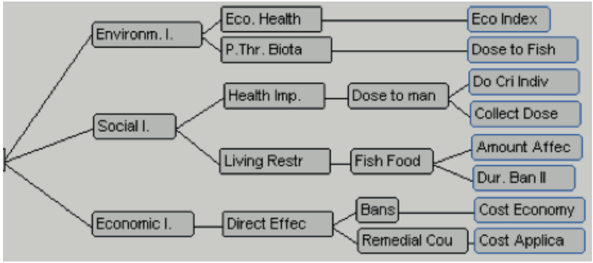


Figure 1. Objective Hierarchy

Environmental Impact (Environm. I.) is one of the main objectives of the decision analysis. It was divided into *Lake Ecosystem Index* (Eco Index), a simple and rational approach for measuring the ecological status of a lake, and *Radiation Dose to Biota* (Dose to Fish). *Social Impact* (Social I.) was handled by two sub-objectives: *Minimizing Impact on Health* (Health Imp.) and *Living Restrictions* (Living restr).

Regarding the health impact, we focused on the *Dose to Critical Individuals* (Do Cri Indiv), who should never receive radiation levels above thresholds for early health effects, and *Collective Dose* (Collect Dose), which was linearly related to the increase in the risk of developing serious latent effects, mainly cancers. As regards living restrictions, other impacts were taken into consideration. These include countermeasures affecting the direct consumption of fish for food or its processing in the food industry, drinking water and water used by the food industry, the use of water for crop irrigation and the recreational uses of water bodies. For all these objectives, the attributes were the *Amount of Fish Affected* by restrictions (Amount Affec), as well as the *Duration of Restrictions* (Dur. Ban II).

Finally, *Economic Impact* (Economic I.) focused on *Direct Effects* (Direct Eff), which included the costs generated by the different bans or restrictions ON normal living conditions, which can be subdivided into *Costs to the Economy* (Cost Economy) and *Application Costs* (Cost Applica), i.e., costs of chemical and physical remedial countermeasures.

The following six strategies were considered for evaluation:

- *No Action*. Natural evolution of the situation without intervention.
- *Potash Treatment*. Reduction of aquatic organism uptake by potash treatment of aquatic ecosystems contaminated by radiocesium.
- *Fertilization*. Tonnes of fertilizer added to the lake to increase biomass.
- *Lake Liming*. Reduction of radionuclide remobilisation from sediments.
- *Sediment Removal*. 6 km^2 of sediments removed from the lake down to depth of 5 cm.
- *Automatic Food Bans*. Automatic fish consumption ban when ^{137}Cs content in fish is greater than 1000Bq/kg.

The impacts of the intervention strategies were then established in terms of the attributes associated with the lowest-level objectives (see Table 2 in Gallego, Jiménez, Mateos, Sazykina, Ríos-Insua, Widengård 2001).

DM preferences were elicited according to the *DA* cycle. An imprecise component utility function was assessed for each attribute, representing DM preferences concerning the respective possible attribute impacts. Figure 2 shows the class of utility functions for *Dose to Fish*.

On the other hand, objective weights representing their relative importance were elicited along the branches of the objectives hierarchy. Then, the attribute weights used in the additive multi-attribute utility model were assessed by multiplying the elicited weights in the path from the overall objective to the respective attributes (see Figure 3). These attribute weights are indicators of the influence of the individual criteria on the decision.

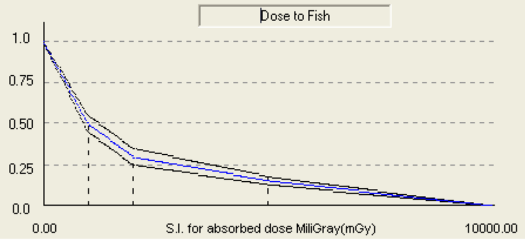
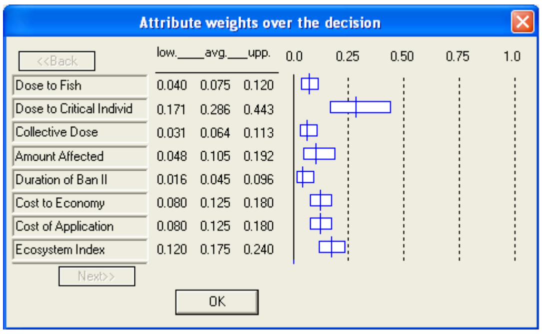


Figure 2. Component Utility Functions for *Dose to Fish*

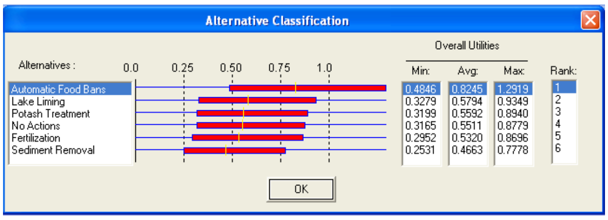


	low	avg	upp.
Dose to Fish	0.040	0.075	0.120
Dose to Critical Individ	0.171	0.286	0.443
Collective Dose	0.031	0.064	0.113
Amount Affected	0.048	0.105	0.192
Duration of Ban II	0.016	0.045	0.096
Cost to Economy	0.080	0.125	0.180
Cost of Application	0.080	0.125	0.180
Ecosystem Index	0.120	0.175	0.240

Figure 3. Relative Importance of Attributes

The additive multi-attribute utility model, which demands precise values, was then used to assess, on the one hand, average overall utilities, on which the ranking of alternatives is based and, on the other, minimum and maximum overall utilities, which give further insight into the robustness of this ranking.

Figure 4 shows the ranking of the intervention strategies for lake Kozhanovskoe, where the vertical white lines on each bar represent average utilities. The best-ranked intervention strategy was *Automatic Food Bans* with an average overall utility of 0.8245, followed by *Lake Liming* (0.5794) and *Potash Treatment* (0.5592), whereas the worst ranked option was *Sediment Removal* with a utility of 0.4663.



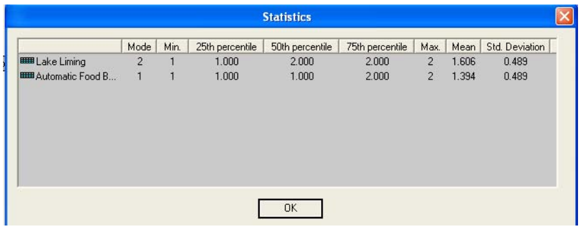
Alternatives :	Overall Utilities Min:	Avg:	Max:	Rank:
Automatic Food Bans	0.4846	0.8245	1.2919	1
Lake Liming	0.3279	0.5794	0.9349	2
Potash Treatment	0.3199	0.5592	0.8940	3
No Actions	0.3165	0.5511	0.8779	4
Fertilization	0.2952	0.5320	0.8696	5
Sediment Removal	0.2531	0.4663	0.7778	6

Figure 4. Ranking of Intervention Strategies

Although *Automatic Food Bans* seemed to outperform the other intervention strategies on the basis of the average overall utilities. But, looking at the utility intervals, the robustness of this ranking is questionable because there is a big overlap between the output intervals, raising doubts about recommending this strategy. Consequently, a SA should be carried out to provide further insight into the recommendations.

First, only two strategies were non-dominated and potentially optimal, i.e., they were not dominated by any other strategy and best-ranked for at least one combination of the imprecise parameters, i.e., weights, component utilities and strategy impacts. Thus, the SA focused the analysis on these strategies, *Automatic Food Bans* and *Lake Liming*. Then, Monte Carlo simulation techniques were applied. Attribute weights were randomly assigned values taking into account the weight intervals provided by the DMs in weight elicitation (see Figure 3). In the 10000 trials performed, *Automatic Food Bans* outperformed *Lake Liming*, i.e., it was best ranked.

Moreover, if attribute weights were generated completely at random, which would mean that there is no knowledge whatsoever of the relative importance of the attributes, then *Automatic Food Bans* would outperform *Lake Liming* by more than 60% (see mean values in Figure 5).



	Mode	Min.	25th percentile	50th percentile	75th percentile	Max.	Mean	Std. Deviation
Lake Liming	2	1	1.000	2.000	2.000	2	1.606	0.489
Automatic Food B...	1	1	1.000	1.000	2.000	2	1.394	0.489

Figure 5. Multiple Bloxplot Statistics

4. SELECTING INTERVENTION FOR THE RESTORATION OF RINGKØBING FJORD

The selection of intervention strategies against eutrophication and the drastic decrease in the bird population in Ringkøbing Fjord was studied at length in (Brhyn, Jiménez, Mateos, Ríos Insua 2009; Jiménez, Mateos, Brhyn, 2011),

Ringkøbing Fjord is a large and shallow brackish lagoon on the west coast of Denmark. It has an area of 300 km^2, a volume of 0.57 km^3, a maximum depth of 5.1 m and a mean depth of 1.9 m. The lagoon receives large (2 km^{3}yr^{-1}) freshwater inputs from the catchment, as well as saltwater inputs through a sluice that connects the lagoon to the sea (see Figure 6).

Ringkøbing Fjord has gone through two environmental regime shifts during the last decades (Håkanson, Bryhn and Eklund 2007), which has stirred up public sentiment in the area, mainly because of the disappearance of waterfowl.

The following nine intervention strategies were considered for analysis:

- *S1: 10% P abatement*. Reducing the *P* input by 10%.
- *S2: 33% P abatement*. Reducing the *P* input by 33%.
- *S3:10% N+P abatement.* Reducing the nutrient input by 10%.
- *S4:33% N+P abatement*. Reducing the nutrient input by 33%.
- *S5: Sluice*. Building a pumping station or another sluice between the lagoon and the sea to increase the saltwater inflow.
- *S6: Salt7.2*. Reducing the salinity to 7.2‰.

- *S7: 10% P abatement + Sluice*. A combination of intervention strategies *S*1 and *S*5.
- *S8: 33% P abatement + Sluice*. A combination of intervention strategies *S*2 and *S*5.
- *S9: No action*. Natural evolution of the situation without intervention

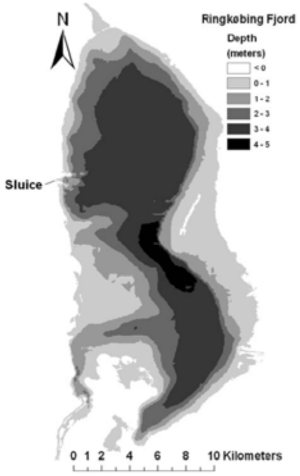


Figure 6: Ringkøbing Fjord

Intervention strategies were evaluated considering their environmental, social and economic impacts (see Figure 7). There were two attributes stemming from the *environmental impact*, *natural TRIX deviation* (N TRIX Dev) and *number of birds* (N. of Birds). The degree of eutrophication in a coastal area can be expressed as a *TRIX* (TRophic state Index) deviation from the background value. The attribute associated with this lowest-level objective represented the average *TRIX* deviation against previous years over a 20-year period.

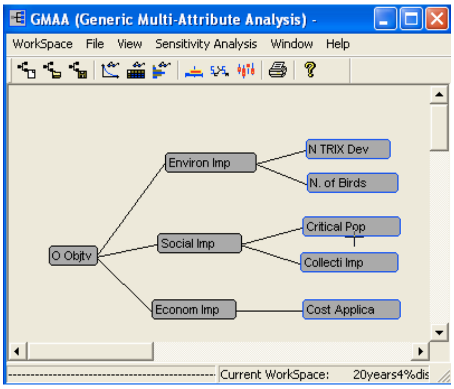


Figure 7. Objective Hierarchy for Ringkøbing Fjord

Another environmental impact we took into account was related to the sharp fall in bird-days over the year in recent decades. The associated attribute accounted for the number of birds representing the average number of Bewick's swans and pintails living in the lagoon in a year for the time period under consideration.

Regarding the *social impact* we made a distinction between the *social impact for critical population* (Critical Pop), i.e., people living around the lagoon that may be affected by the application of intervention strategies, and *collective social impact* (Collecti Imp). Both subjective attributes account for aspects like sentiment, possible employment associated with strategy application, crop image…

Finally, the *economic impact* was computed by the average costs concerning the intervention strategy application (Cost Applica), i.e., nutrient abatement costs and/or construction and maintenance costs for facilities.

Note that while the models or experts initially provided precise performances, imprecision was introduced by means of an attribute deviation of 10% to evaluate the robustness of the evaluation (see Table 4 in Jiménez, Mateos, Brhyn, 2011).

Next, the DMs' preferences were quantified. This implies assessing, on the one hand, component utilities in attributes that represent the DMs' preferences concerning the possible intervention strategy impacts, and, on the other, local weights, which represent the relative importance of criteria in the objective hierarchy.

Regarding the utility function corresponding for the *natural TRIX deviation* attribute, the background *TRIX* of 4.3–5.1 was estimated. This was used as a baseline for optimal conditions in this study. On the other hand, *TRIX* in 1990–1993 was 6.3. This was identified as the least preferred value. Taking into account that the attribute represents the average *TRIX* deviation against previous years over a 20-year period and the above information, attribute values between [0, 0.4] were assigned a utility 1. Then, the utility function was linearly decreasing in the range [0.4, 1.6], and for any average deviation greater than 1.6, the associated utility was 0 (see Figure 8).

Regarding the *number of birds*, the component utility function is straightforward. The best attribute value is assumed to be 100,000 birds (Bewick's swans and pintails) and the worst one is 0 (no birds). Consequently, the utility function is increasing. For a description of the component utilities function corresponding the remaining attributes, see (Jiménez, Mateos, Brhyn 2011).

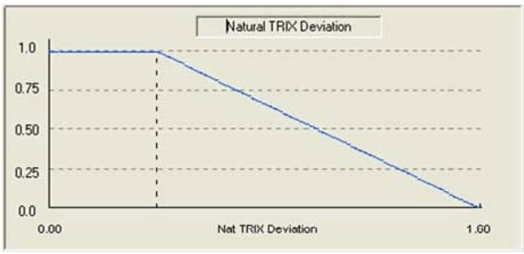
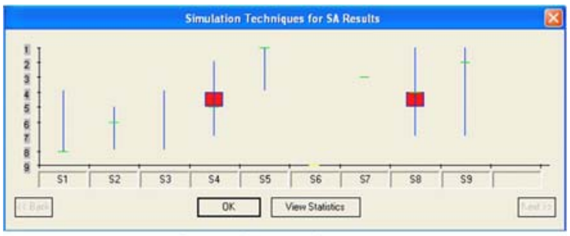


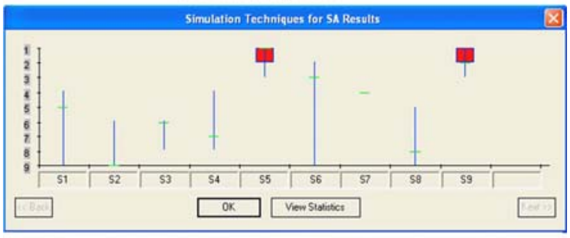
Figure 8: Component Utility Function For *Natural TRIX Deviation*

On the other hand, the ecocentric, anthropocentric and tax-refuser perspectives were used to elicit different weight sets. A pure ecocentrist would assign a weight of 100 to environmental impacts. However, a pure anthropocentrist would assign no weight to the environmental impact but distribute all the weights across the social and economic impacts. Finally, a persistent tax-refuser would assign total weight to the economic impact and no weight to social or environmental impact. Shrivastava (1995) and Rauschmayer (2001) give reasons why different perspectives may be needed can be found.

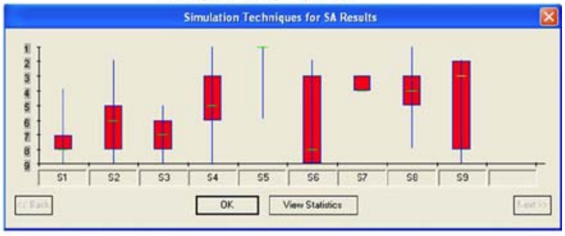
Finally, Monte Carlo simulation techniques were applied. They can be useful for analyzing the intervention strategies from the ecocentric and anthropocentric perspectives. The attribute weights were selected at random, and the computer-simulated ranking of attribute importance from different perspectives was stored to efficiently explore the results of many weight combinations. Figure 8 shows the resulting multiple boxplots.



Ecocentrist perspective



Anthropocentrist perspective



Tax-refuser perspective

Figure 8: Strategy Evaluation From Different Perspectives

Looking at the multiple box plots for the ecocentric and anthropocentric perspectives, we find that *S*5: *Sluice* and *S*9: *No action* are ranked highest in both boxplots. *S*8: 33% *P abatement* + *Sluice* is ranked highest from the ecocentric viewpoint, but its best ranking from the anthropocentric perspective is fifth. Finally, *S*6: *Salt7.2*, with a best ranking of second from the anthropocentric viewpoint, is ranked as the worst strategy from the ecocentric perspective. *S*5: *Sluice* and *S*9: *No action* look better than the others. Moreover, the average rankings for both are 1.011 and 2.489 from the ecocentric perspective, respectively, and 1.531 and 1.605 from the anthropocentric viewpoint. These results are even consistent with the tax-refuser perspective, in which *S*5 is better ranked (average ranking 1.246) than *S*9 (average ranking 4.621). Thus, we arrived at the conclusion that *S*5: *Sluice* was the intervention strategy to be recommended.

Moreover, if we assume that there is no knowledge whatsoever of the relative importance of the attributes, i.e., weights for the attributes are generated completely at random, *S*5: *Sluice* was again the best intervention strategy throughout the simulation.

The same methodology was applied for different interest rates (0, 2, 4, 6, and 8%), and we arrived at the same conclusion that *S*5: *Sluice* was the intervention strategy to be recommended.

5. CONCLUSIONS

Most environmental decision-making problems have multiple conflicting objectives and are usually plagued with uncertainty, being impossible to predict with certainty what the consequences of each strategy under consideration will be.

The GMAA system is a decision support system that to allay many of the operational difficulties involved in a decision-making problem by helping decision makers to structure and achieve a better understanding of the problem to make a final decision.

Two examples illustrate the application of the GMAA system and prove that sensitivity analysis tools can be useful to provide further insight into the recommendations.

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