MULTI-OBJECTIVE DECISION SUPPORT INCLUDING SENSITIVITY ANALYSIS

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Summary

The article presents a methodological background of multi-objective decision support and its applications to environmental decision-making problems. It starts with discussing basic concepts of model-based decision support by outlining the characteristics of modern decision makers and presenting in more detail possibilities and limitations of operational research methods by providing useful support for actual decision making processes. In particular, methods of formulation and analysis of mathematical models that allow for their efficient use for decision support are described.

The article concentrates on one of the most efficient ways of model analysis for decision making support, namely on multi-objective model analysis methods. These methods are

summarized and illustrated by a software tool, which has been widely used in various environmental applications of actual decision making support. The relations between these methods and two basic classical methods of model analysis, namely simulation and single-objective optimization are discussed. One particular method of multi-objective model analysis, namely aspiration-reservation based model analysis is discussed in more detail and illustrated by an outline of its implementation. Presentation of multi-objective model analysis methods finishes with an overview of methods specialized for multi-criteria analysis of a small set of alternatives.

The article also outlines a general structure of model-based decision support systems, which is based on actual implementations of the methods presented to real-world environmental policy problems of various scales applied to several problems, including the quality of air and water, and to land use planning.
Finally, advantages and limitations of model-based decision support are briefly summarized.

1. Introduction

The complexity of environmental problems requiring rational decision making and of the decision making process have been growing rapidly. Globalization, interlinks between environmental, industrial, social and political issues, and the rapid speed of change all contribute to the increase of this complexity. While decision-making is becoming more and more difficult, especially for environmental problems, there are methodologies and tools which,when used properly,can greatly assist modern decision makers in making better decisions.

However, these methods and tools are not available in a form ready from the shelf that can easily be adopted for supporting decision making in complex problems. They are, rather, components which can be used by skilled teams of modelers, who can develop in a close collaboration with future users, a problem specific Decision Support System (DSS). A skilled team of modelers is needed because heterogeneous knowledge about decision making processes and their support is rapidly increasing, and therefore a rational selection of methods and tools that are appropriate for a specific problem requires expertise in several fields. Moreover, a large spectrum of approaches presented in the literature is typically illustrated only by simple examples, and the range of their applicability is often exaggerated. Therefore, integration of model-based decision support methodologies and tools with specialized model-based knowledge developed for handling real environmental problems is needed. In addition, these typically need to be considered together with the corresponding engineering, industrial, economical, and social and political activities which require various skills from an interdisciplinary team.

Environmental decision problems always require a multi-objective approach because they typically involve analysis of trade-offs between conflicting objectives, such as various costs and indicators of the state of environment. Depending on the type of the decision problem, different methods of multi-criteria problem analysis are appropriate from the methodological point of view. However, the habitual domain of a Decision Maker (DM) is a far more important factor for the selection of methods than their theoretical correctness. In reality, the decisions are made by DMs, and not by the developers of DSSs. Therefore a DSS will be used only if the implemented methods and assumptions will be understood and accepted by those who actually make the decisions and take responsibility for the consequences of their implementations. Moreover, the developers of a DSS have to understand the decision making process and its environment, which is always specific for each problem. This is why close the collaboration between the developers of a DSS and a DM is one of the necessary conditions for a proper design and implementation of each DSS. It also justifies the observation that no tool ready from the shelf can actually be applied to support decision making in a complex problem.

This article starts with a summary of basic concepts of model-based decision support. Then it presents in more detail methods and tools for multi-objective model analysis for decision support. Finally, the advantages and limitations of model-based decision support are summarized.

2. Basic Concepts

2.1. Modern DM

A selection of methods and tools for supporting decision making is to a large extend determined by the characteristics of the people, who need and want to use such support. Therefore, one should start with an outline of such characteristics.

For the sake of brevity, by Decision Maker (DM) we understand here not only those people who actually make decisions or take part is a Decision-Making Process (DMP) but also experts, advisors, analysts, even researchers: in other words anybody who uses analytical methods for decision analysis. The word "modern" stresses two facts: first, as already discussed in the Introduction, that rational decision making is becoming more and more difficult; second, that the developments in decision support methods and tools nowadays offer help for comprehensive analysis of various aspects of the problem at hand, including examination of possible outcomes of various decisions and identification of decisions that best correspond to a preferential structure of a DM.

Any DM wants to understand in the best possible way the consequences of implementations of his/her decisions before making the final selection of a decision. Moreover, especially in more complex situations, a DM typically needs help in finding decisions that correspond best to her/his preferences. The preferences can rarely be precisely defined in advance because they often change while a DM learns about the decision problem. Experiences show that such learning is an important element of the development and use of a DSS for any complex problem, for which intuition and expertise of a DM are not enough for predicting consequences of various decisions. Finally, a DM typically also wants to examine consequences of decisions that he/she defines, often by using his/her own intuition and/or experience for modifications of decisions obtained from other analysis or suggested by somebody else.

A modern DM is confronted with more complex decision problems than previous generations of DMs, but she/he has much better knowledge about decision making processes and access to analytical tools and teams of experts and advisors. Therefore, such a DM is not fond of accepting the classical OR approach based on using a given solution of a mathematical model which represents a well-structured problem as the basis of a decision. He/she needs a DSS which can be used for various types of analysis which can help to extend the DM's knowledge about the problem and allow him/her to take advantage of his/her experience and intuition. In order to achieve this, a good DSS can be considered as being composed of two mutually linked parts that are of different nature:

- A mathematical model that represents a part of DMP which have logical and physical relations that have to be considered for a given decision problem, but which should be handled in a form of a model rather then by intuition or experience of a DM. Such a model is subsequently called a core model.
- Tools for a comprehensive analysis of a core model.

2.2. Core Model

Mathematical and computer models are widely used in many areas of science and industry for predicting the behavior of a system under particular circumstances, when it is undesirable or impossible to experiment with the system itself. The understanding of the system gained through a comprehensive examination of its model can greatly help in finding decisions (controls) whose implementations will result in a desired behavior of the system.

The systems that are modeled have very different characteristics (including the nature of the underlying physical and/or economical processes, their complexity, size, types of relations between variables). There is also a great variation in the use of models, which depends on various factors (like the decision making process, the background and experience of model users). However, the modeling process (composed of problem formulation, model specification, implementation, verification and validation, analysis and management) also has many similarities when the modeled systems are very different. The modeling process is a combination of craftsmanship and art, and its quality is critical for any model-based DSS. However, a discussion of the related issues is far beyond the scope of this article: a reader interested in these issues is advised to consult some of the references listed at the end of this article.

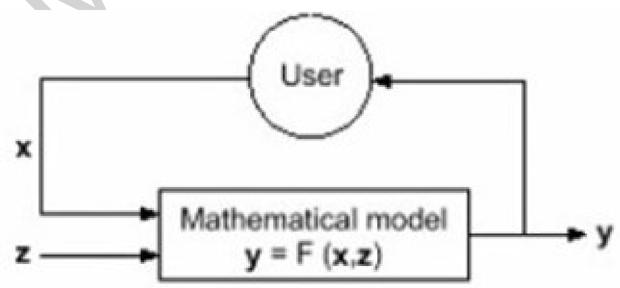

Figure 1. A mathematical model represents relations between decisions (inputs) **x**, external decisions (inputs not controlled by the user) **z**, and consequences (outcomes) **y**.

Only basic concepts and features of a core model, which are essential for the explanation of model-based decision support are discussed here. The basic function of a core model is to provide an evaluation of the consequences that will result from an implementation of given decisions. All four basic concepts illustrated in Figure 1, namely decision variables, external decisions, outcome variables and a mathematical model are briefly discussed in the following subsections.

2.2.1. Illustrative Examples

In order to illustrate several concepts discussed in this article we outline here two actual DSSs, which are presented in more detail in article *Decision Support Systems for Environmental Problems at Different Scales*.

The first model, referred to as RWQM (from Regional Water Quality Management), is applied to a region in which untreated or inadequately treated municipal and industrial wastewater emissions should be reduced in order to improve ambient water quality. At each discharge point, one technology out of a set of possible technologies can be implemented in order to meet the desired water quality goals in the region. In this selection of technologies, or strategy development, decision makers must evaluate the trade-offs among a large number of alternatives based on, among other things, effluent and/or ambient water quality standards and goals, as well as capital investment and annual operating costs.

The second model, RAINS provides a consistent framework for the analysis of emission reduction strategies, focusing on acidification, eutrophication, and tropospheric ozone. RAINS comprises modules for emission generation (with databases on current and future economic activities, energy consumption levels, fuel characteristics, etc.), for emission control options and costs, for atmospheric dispersion of pollutants, and for environmental sensitivities (i.e.,, databases on critical loads). In order to create a consistent and comprehensive picture of the options for simultaneously addressing the three environmental problems (acidification, eutrophication, and tropospheric ozone), the model considers emissions of SO_2, NO_x, ammonia (NH_3), and VOC.

RWQM is a rather small (composed of about 1 000 variables) MIP type model, and RAINS is a large (about 30 000 variables) non-linear model. Both of them have been used for supporting complex decision making processes, and they illustrate well various issues of model-based DSS.

2.2.2. Decision Variables

In model-based decision support it is assumed that decisions have quantitative characters and therefore can be represented by a set of the model variables, hereafter referred to as decisions, $x \in E_x$ where E_x denotes a space of decisions. In a trivial case $x \in R$, which denotes that a decision is represented by a real number. However, in most cases x is a vector composed of various types of variables. For larger problems the components of x are aggregated in several vectors. Let us illustrate this by specification of the decision variables of our illustrative models.

In the RWQM model, the decision variables are the treatment technologies to be implemented at the nodes where waste-water emissions occur. A selection of technology is represented by a binary variable x_{jk} (which takes the value of 1, if a corresponding technology is selected, and the value of 0 otherwise), k is the technology choice at emission node j. These technology options include the option of no treatment (with raw waste concentrations and no cost, which is actually only a theoretical alternative since minimum treatment levels would likely be required), as well as the option of maintaining the existing technology (with the operating cost but no investment cost). Therefore, formally, the decision vector x is composed of vectors x_j , each of which is a vector of binary variables. This convention is of course used only for modelers. Results are provided for users of the RWQM with the help of a map, which shows a description of a selected technology for each location.

In the RAINS model the main decision variables are the annual emissions of the following four types of primary air pollutants from either sectors or countries:

- n_{is}, annual emission of NOx from sector *is*;
- v_{is}, annual emission of nonmethane VOC from sector *is*;
- a_i, annual emission of NH3 from country i; and
- s_i, annual emission of SO2 from country i

where sectors *is* are grouped for each country.

Additionally, optional decision variables are considered for scenarios that allow limited violations of air quality targets. For such scenarios, variables corresponding to each type of considered air quality targets are defined for each receptor. Each variable represents a violation of a given environmental standard. Optionally, violations of targets can be balanced with surpluses (understood as the difference between a target and its corresponding actual concentration/deposition).

2.2.3. External Decisions

Figure 1 illustrates two types of inputs to the core model: decision variables, **x,** controlled by a user, and external decisions denoted by **z**. In practice, **z** inputs may include representations of various quantities that substantially influence the values of outcomes **y** but are not controlled by the user, for example:

- Regulations or commitments to environmental standards for air or water quality management models.
- Meteorological conditions assumed for modeling physical relations in environmental models, e.g., *average, wet, dry, worst* year data for a water model.
- Forecasts of changes in demand for services, e.g., in telecommunication or transportation models.

In the RWQM and RAINS models the external decisions, **z,** are represented by:

- Values representing the environmental standards that define constraints for various indices (such as maximum concentrations of various water and air quality indicators, respectively).
- The set of meteorological data used for calibration of a respective model.

While the external decisions are beyond the control of the user of a DSS, he/she typically wants to examine a range of scenarios with various representations of external decisions in order to find not only a solution which will best respond to a most likely representation of external inputs, **z,** but also a solution that will be robust, i.e., will also be good for various other compositions of **z** that could be considered.

2.2.4. Outcome Variables

The consequences of implementation of various decisions, x, are evaluated by values of outcome variables $y \in Ey$. In various fields of applications, outcome variables are named differently, e.g., outcomes, metrics, goals, objectives, performance indices, attributes. In RWQM there are two sets of outcome variables:

- Three types of costs (investment, operating and maintenance, and total annual cost) related to the implementation and operation of a given selection of water treatment technologies.
- Several types of water quality indicators, such as an extremum (over the set of monitoring points) of concentrations of CBOD (carbonaceous biochemical oxygen demand), NBOD (nitrogenous biochemical oxygen demand) NH_4 (ammonia), DO (dissolved oxygen); depending on the type of a water quality constituent, as the extremum either minimum (e.g., for DO) or maximum (for NBOD, CBOD and NH_4) are taken.

In the RAINS model one outcome variable represents the sum of costs of reductions of emissions; four sets of additional outcome variables correspond to various indices of air quality. While the definition of the cost is rather simple, an appropriate definition of air quality indices is rather complex. Environmental effects caused by acid deposition, excess nitrogen deposition (described by a two-element linear critical loads function), and by eutrophication are evaluated at each receptor by a PWL (piece-wise linear) function that represents an accumulated excess over the threshold of the environmental long-term target. If optional violations of environment standards are allowed, then a maximum (over a set of receptors) violation of each type of air quality indicator is also considered as an output variable.

2.2.5. Objectives

Out of the set of outcome variables $y \in Ey$ a user can select a subset of objectives $q \in Eq$ where E_q is a space of objectives. Quite often objectives are referred to as criteria, and in this article these two terms will be used interchangeably.

Usually E_q is a subspace of E_y, that is, the DM select some criteria q_i from the set of outcomes y_j . Sometimes, also some of the decision variables x are used as criteria, but for the sake of consistency we assume that such a variable is simply represented by one of the outcomes y. Such a set of objectives is typically modified during model analysis. A partial preordering in E_q is usually implied by the decision problem and has obvious interpretations, such as the minimization of costs competing with the minimization of pollution. However, a complete preordering in E_q cannot usually be given within the context of a mathematical programming model. In other words, it is easy to determine, for each objective separately, which solution (represented by vectors x and q) is the best one. However, for conflicting objectives there are two sets of solutions:

- Pareto-optimal (often called efficient), i.e., a solution for which there is no other solution for which at least one criterion has a better value while values of remaining criteria are the same or better.
- Dominated, i.e., solutions which are not Pareto-optimal.

Obviously, a Pareto-optimal solution is preferred over any dominated solution (assuming that the selected criteria correspond well to the preferential structure of a DM). However, a set of Pareto-optimal solutions (often called Pareto-set, or Pareto frontier) is typically composed of an infinite number of solutions, many of which are very different. Pareto-optimal solutions are not comparable in a mathematical programming sense, i.e., one cannot formally decide one is better than another one.

However, DMs are able to express their own preferences for various efficient solutions. One of the basic functions of multi-objective decision support is to provide the various ways by which a DM may specify his/her preferences. There is no reliable formal way for separating a specification of preferences from a process of learning from the model analysis. It is a commonly known fact that decision making is not a point event, even in situations where it is realistic to assume that the problem perception does not change during the DMP. Therefore, the possibility of using a DSS in a learning and adaptive mode is a critical feature.

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Biographical Sketch

Marek Makowski's background is Control Engineering, Computer Science and Applied Mathematics. My current research interests include applications of mathematical programming methods and of relevant user interfaces in decision support systems, the development of methodology, algorithms, and software for decision support using multicriteria optimization.

I graduated in 1970 from the Faculty of Electronics of the Warsaw University of Technology in the field of automatic control and computer sciences. I had also studied mathematics at the Warsaw University. In 1970 I joined SRI (the Systems Research Institute of the Polish Academy of Sciences). I received my Ph.D. in 1976 from the Polish Academy of Sciences for a thesis on the optimization of environmental models. Before joining IIASA in 1987 I had been a leader of the project on the development of decision support systems for various applications in Poland, and since 1976 I had been actively participating in joint projects with IIASA.

I joined the Computer Services Department of IIASA in August 1987 to work on the development and application of mathematical programming software. I was Acting Project Leader of the Methodology of Decision Analysis (MDA) Project from September 1989 until August 1991, and since then I have been a member of this project. As of January 1997 I have continued the activities I had been doing within the MDA Project (which terminated at the end of 1996) within the new Risk, Modeling and Policy Project. During my affiliation with IIASA, I am on leave from the Systems Research Institute of the Polish Academy of Sciences.