Environmental application of the Feasible Goals Method: Screening of water quality improvement strategies

A. Lotov [1]
L. Bourmistrova [1]
R. Efremov [1]
V. Bushenkov [2]

[1] Computing Center, Russian Academy of Sciences, Vavilova, 40, Moscow - Russia,
email: lotov@ccas.ru;
[2] University of Evora, Evora, Portugal;

Abstract. Multiple-criterion screening of environmental decision strategies in the framework of decision support system for water quality improvement is described. Screening technology is based on integration of diverse knowledge and information on water quality processes and on application of the Feasible Goals Method for exploration of the integrated model. The Feasible Goals Method provides graphic display of aggregated decision information that informs decision makers on efficient tradeoffs among screening criteria and helps to select preferable decision alternatives by identification of feasible goals directly on display. The DSS was developed on request of Russian Ministry of Natural Resources in the framework of the Federal program “Revival of the Volga River”.

Key words: multiple criteria decision screening, Feasible Goals Method, DSS

1. Introduction

The decision support technology discussed in the paper is applied in the framework of DSS that is used at the early screening stage of a decision process. Screening is aimed at a search for a small number of decision alternatives, which are a subject of further detailed exploration during the process of final selection of water quality improvement projects.

Computer graphic tools play an important role in supporting decision processes. However, they concentrate now on the stage of the final analysis and choice. Since the final decision making stage usually consists in simulation of comprehensive mathematical models combined with a detailed exploration of simulation results, modern graphic tools can be extremely helpful. Multimedia tools, virtual reality, and geographic information systems, which provide decision makers with exciting opportunities of rapid graphic assessment of one or few decision alternatives, find their proper place in real-life decision processes.

In contrast, the screening stage usually is not supported with modern graphic tools. Decision makers have to design decision alternatives by themselves guided by their experience and feelings. An attempt to support decision screening by using the single-criterion optimization actually failed since this technique turned to be not able to incorporate intuition and interests of decision makers. So, decision makers still have to solve the problem by themselves. Often, experts are asked to select a small number of alternatives for further detailed exploration. Expert involvement saves time for decision makers, but introduces additional complications related to the fact that the alternatives developed by experts usually reflect their experience, perceptions, and goals, which may differ from those of decision makers. It can result in a deadlock during the final stage since decision makers are forced to choose among strategies that do not reflect their opinions or interests. Therefore, a new information technology is needed that can amplify experience and intuition of decision makers through application of computer-based techniques at the screening stage. In this paper we describe a technology of this kind and outline its application in the DSS for water quality planning.

It is important to note that the final stage of decision making is often a negotiation process that involves several (or even multiple) decision makers with different interests and goals. In this case, screening plays the role of the negotiation preparation. On this stage, negotiators may want to find such decision alternatives that are preferable for them and acceptable for other negotiators. These pre-negotiation activities are separated from the final negotiations. The time requirements are not so restrictive as in the case of search for final agreement. Say, the screening stage can last for months and even years in the case of environmental planning. Due to this, multiple stakeholders, independent institutions and political groups, as well as experts associated with them, take part in screening activities. For this reason, decision screening must be transparent and simple. In particular, multiple questions concerning decision maker's preferences must be avoided. On the contrary, diverse knowledge and information on decision situation must be processed as much as possible to provide decision maker with decision information in a refined integrated form.

To fulfill the above requirements, we integrate original knowledge and information and construct a simplified integrated model of an environmental decision problem. Then, a special technique for processing the integrated model (Feasible Goals Method, FGM) is applied that results in graphic display of aggregated decision information and helps to select preferable decision alternatives by identification of feasible goals directly on display. This technology for screening of environmental strategies was introduced in (Lotov 1994 and 1998). Opportunities of its application for water quality planning was discussed in (Lotov et al. 1999a). Here, we report the results of application of the technology.

In Section 2, main features of the technology are introduced. Section 3 describes preparation of integrated model. Application of the FGM for the processing of the integrated model and user's preference information are described in Section 4. DSS for water quality planning is described in Section 5.

2. Main features of the technology

The need for a computer-based support of decision screening procedures was discussed in engineering fields for many years. Say in water management, importance of decision screening was stressed by R.Dorfman as soon as in 1965 (Dorfman 1965) who articulated a role of simplified mathematical models in decision screening. Indeed, decision screening usually requires the integration of knowledge from a number of diverse disciplines. In water quality planning one has to describe wastewater discharge, wastewater treatment, pollutants transport, effect of pollution, and so forth. Simulation of detailed models can not help to explore the whole lot of possible strategies. Therefore, integrated models are needed. Due to further studies of decision alternatives selected on the screening stage, an integrated model may be simplified and fairly rough. The most important requirement that must be met by the model – it should describe all important features of the decision situation. We apply this idea and use expert knowledge and other information for preparation of data of an integrated model.

Integrated models are used in the DSS to approximate the so called Edgeworth-Pareto Hull (EPH), i.e. the variety of feasible combinations of criterion values broadened by all dominated criterion points. The EPH is used for graphic display of efficiency frontiers and for selecting a small number of decision alternatives. We provide a free interactive display of the efficiency frontiers in the form of decision maps that are collections of efficiency frontiers among pairs of decision criteria. A specially developed software, the Interactive Decision Maps (IDM), provides pictures that qualitatively inform on potentially feasible combinations of values of three to seven selection criteria values and, what is especially important, on efficient criterion tradeoffs. The colorful display can influence mental models of users on the logical level, on the level of images and, hopefully, on the subconscious level.

Selecting of a preferable strategy is based on the Feasible Goals Method (FGM) that is a special form of preference information processing. Only at this step user has to identify his preferences in the form of a preferable combination of criterion values (a goal). The goal is identified by a click of computer mouse on a decision map. Since the goal is feasible, a decision alternative can be found, output of which coincides with the identified goal. So, user is asked about preference information to a minimal extent. As result, a preferred decision alternative is selected. The selecting procedure is fairly transparent since it is reduced to identification of a feasible goal, for explanation of which decision maps can be used. One can see that the technology is fairly generic and can be applied in various environmental DSS. Here, we illustrate it on the basis of its application in a DSS for water quality planning in large rivers.

3. Constructing the integrated model

The process of constructing an integrated model can be based on integration of simplified descriptions of the subsystems of an environmental system. Often a simplified description can be derived from an original mathematical model of the subsystem. In this case, one has first to transform rough knowledge and information into the data of the original model (to calibrate the original model). Methods for calibrating the original models are not considered here, since they depend mainly upon the field of science to which the model belongs. After an original model has been calibrated, one can start development of a simplified model. Often a simplified description has a form of one or several influence matrices, i.e. matrices that relate outputs of the model to its inputs. The most universal way to construct an influence matrix is parameterization of the original model, i.e. providing an approximation of its input-output dependencies.

The integrated model used in the DSS includes three sub-models:

1. a pollution transport sub-model that provides an opportunity to compute the concentration of pollutants in monitoring points for given discharge,
2. a wastewater discharge sub-model that describes the volume and structure of the discharge attributed to a particular region, river segment and industry,
3. a wastewater treatment sub-model that relates the decrement of wastewater discharge to the cost related to constructing and performance of the wastewater treatment installation.

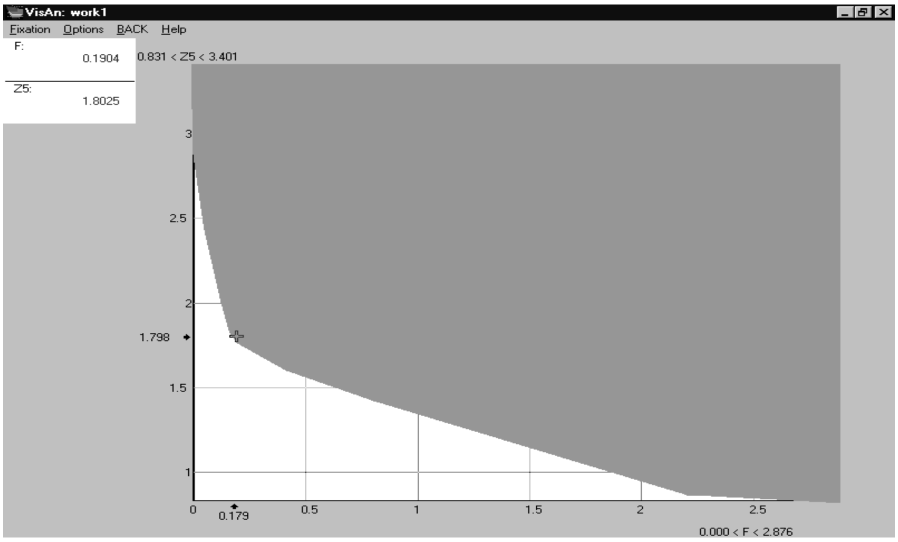
Simplified description of the first subsystem was based on influence matrices for particular pollutants. Constructing of them was based on the application of the well-known system for modeling of rivers and channels MIKE 11. The detailed pollution transport model was developed first. Constructing of the influence matrices was based on its simulation. Six influence matrices for particular pollutants describe pollutant transport and are used to relate the decrement of the wastewater discharge to concentration of the pollutants at monitoring stations in the integrated model used in the DSS.

The simplified model of the wastewater discharge treatment used in the DSS was based on the concept of wastewater purification technologies elaborated by experts. The wastewater discharge was described on the basis of a collection of parameters partially based on discharge reports received from the industrial enterprises and municipal authorities. Influence matrices, technological matrices, balance equations, and discharge data constituted the integrated model. Decision variables of the integrated model were the investment strategies that described investment into particular purification technologies in particular regions. The integrated model is used in the DSS for the display of aggregated decision information, graphic exploration of which helps user to identify a preferable feasible goal that defines results of decision screening.

4. Graphic tradeoff analysis and goal specification

It is supposed that user selects two to seven screening criteria. Application of the FGM is based on previous exploration of efficiency frontiers among pairs of criteria provided by the IDM technique. We introduce it first informally, on the basis of examples. Let us start with the case of two screening criteria:

1. the total cost of the project (F, in billions of US$), and
2. the maximal concentration of oil products in the river (Z5, in relative units).



F: 0.1904

Z5: 1.8025

Fig. 1. Feasible values of two criteria are given by the shaded area

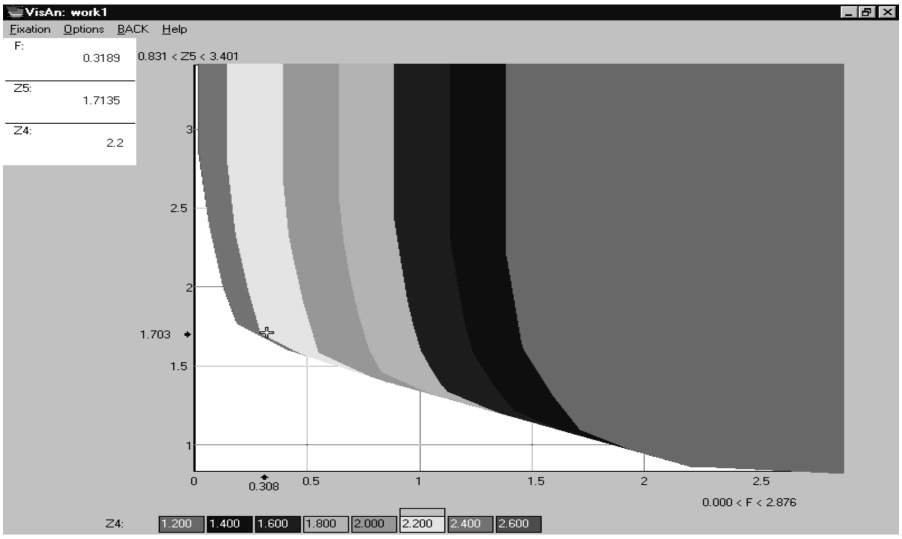
In Fig. 1 the values for the pollution criterion are given along the vertical axis, and values for the total cost are given along the horizontal axis. The feasible combinations of criterion values and criterion points that are dominated by them are given by the shaded (colored in computer display) area. The combinations outside the shaded area are not feasible. If one takes into account that the decrement of both criteria is of interest, the frontier of the shaded area (so called efficiency frontier or efficient criterion tradeoff curve) provides the decision information: comparing two points of the frontier, user understands the additional payment related to the decrement of pollution if efficient decisions are applied. For example, one can see that the pollutant concentration can be decreased substantially from its maximal value Z5=3.4 till Z5=1.8 for the cost of only $190 million (this point on the efficiency frontier is given by the cross, and its precise location is given in the box in the upper left corner). So, about one half of the possible pollution decrement is provided only by 7% of the maximal investment!

Further investment, however, is not so efficient: the slope of the frontier changes drastically in the vicinity of the cross. One can easily estimate that the pollutant concentration about Z5=0.85 can be achieved for not less than $2.2 billion, and the rest of investment (about $700 million!) is practically inefficient. So, a simple-minded minimization of the pollution level results in wasting of the money!

The idea to compute and display the efficiency frontier was introduced for two criteria by S.Gass and T.Saaty (1955) and transformed into a generic approach to multiple criterion decision problems (methods for non-inferior frontier generation) by J.Cohon (1978). The IDM technique develops the idea of Gass, Saaty and Cohon for the case of multiple criteria (three, four, five, six, and even more). Since the number of criteria is larger than two, different display is used.

Let us add now a third criterion – the maximal concentration of nitrates in the river denoted by Z4. The relation among cost and oil pollution Z5 depends now on the value of Z4.

Exploration of the influence of Z4 can be started by animation of the efficiency frontier among cost and Z5. Since it is impossible to show it here, we can advise to download the demo software from our Web page (http://www.ccas.ru/mmes/mmeda/soft). Instead, we display here the superimposed snap-shots of such animation – a decision map (Fig. 2).



F: 0.3189

Z5: 1.7135

Z4: 2.2

Fig. 2. Decision map

The value of Z4 is given by shadings (color on display). Relation among value and shading is provided in the palette under the decision map. A decision map thus plots the efficiency frontiers among two criteria, for several restrictions imposed on the value of the third criterion. By this, a decision map provides a rough guide on the efficiency tradeoffs among three criteria. The quantity of the additional nitrates-oriented investment can be measured by the width of the strips. One can see that the additional cost related to the decrement of Z4 from 2.6 to 2.2 is relatively small if Z5 is about 1.7. Further decrement of Z4, however, requires a larger cost. More than $200 million are needed to decrease the value of Z4 from 2.2 to 2.0 if Z5 is about 1.7.

Standard decision map technique displays several cross-sections of the multiple-dimensional efficiency frontier of the EPH. Though the display used in the IDM technique is fairly similar, it has several advantages, the most important of which is related to the method how the decision maps are computed. To discuss this topic, we introduce the method mathematically. Let the variety of feasible decisions $X \subset W$ be given, where W is a decision space (finite-dimensional linear space R^n, in our case). Let the decision x be related to criterion vector y, which is the element of linear finite-dimensional space R^m, by a given mapping $f : W \to R^m$. Then, the variety of attainable criterion vectors is defined as

$$Y = \left\{ y \in R^m : y = f(x),\, x \in X \right\}.$$

Let us suppose that user is interested in minimizing the criterion values. In this case a criterion point y' dominates (is better than) a criterion point y, if and only if $y \geq y'$ and $y' \neq y$. Then, the non-dominated (efficient, Pareto-optimal) frontier of the variety of feasible criterion points Y is defined as a variety of non-dominated points $y \in Y$, i.e.

$$P(Y) = \{ y \in Y : \{ y' \in Y : y' \leq y,\, y' \neq y \} = \varnothing \}.$$

The Edgeworth-Pareto Hull (EPH) of Y is defined as $Y^* = Y + R^m_+$, where R^m_+ is the non-negative cone of R^m. It is important that the non-dominated frontiers of Y and of its EPH coincide, but the dominated frontiers disappear in the EPH. The EPH for two criteria is depicted in Figure 1 by the shaded area.

The IDM technique consists in approximation of the EPH for any number of criteria and in interactive display of decision maps (collections of two-criterion efficiency frontiers), which are computed as the frontiers of two-dimensional slices of the EPH. Decision maps can be computed and depicted on-line, since the EPH has been approximated in advance. In the convex case, approximation of the EPH is based on methods that combine the methods for convolution of linear inequalities introduced by Fourier and optimization techniques. Short description of the convolution-based algorithms is given in Lotov (1996). Detailed description of the algorithms is given in Russian (Lotov et al. 1999b). Though we restrict with linear models in this paper, the non-linear multiple-criterion problems can be explored as well (Lotov et al. 1999b).

In three-criterion problems, the IDM technique may be used to provide arbitrary arrangement of criteria in decision maps, to squeeze the criterion ranges, to change the number of tradeoff curves and to zoom a map. Due to this, user can assess relations among three criteria. Application of the IDM technique is even more important if four, five and more criteria are used. In this case values of the fourth, fifth and other criteria are specified by positions of thumbs of scroll bars located under the decision map. The influence of these criteria can be studied by manual movement of the thumbs or by animation of a decision map, i.e. automatic movement of the thumbs. User can easily require any animation of any of decision maps. Moreover, matrices of decision maps related to several values of the fourth and the fifth criteria can be displayed. Such matrices can be animated for exploration of the influence of the sixth criterion. These opportunities help decision maker to assess relations among all criteria.

Once exploration of a decision map is completed, user is supposed to identify a feasible combination of criterion values (feasible goal). A preferred feasible goal can be identified on a decision map with a click of computer mouse. For example, the cross that is displayed in Figure 2 may be identified as a feasible goal. Note that the goal is the only information provided by user. This feature differs the FGM from different interactive multiple criteria decision support techniques. From the other point of view, the FGM differs from the standard goal methods – now the identified goal is feasible! This means that there exists a decision alternative that results in the identified goal. It usually takes only several minutes to compute such an alternative. Detailed description of the FGM is given in Russian (Lotov et al. 1999b) and in several papers in English, for example, in (Lotov et al. 1997; Lotov et al. 1999a).

5. DSS for water quality planning in large river basins

The DSS for water quality planning contains seven subsystems:

1. subsystem for preparation of data for the integrated model,
2. subsystem for visualization of the current pollution,
3. subsystem for specification of decision criteria and restrictions imposed on performance indicator's values,
4. subsystem for approximation the EPH,
5. subsystem for interactive and animated display of decision maps and identification of a feasible goal,
6. subsystem for computing a goal-related strategy,
7. subsystem for visualization of the computed strategy in GIS.

The system was developed on the request of the Russian Ministry for Natural Resources in the framework of the Federal program "Revival of the Volga River". The role of the subsystems is clear from their names. Only two short comments are needed.

First, user has to specify preferable screening criteria in a large list of performance indicators (potential criteria) in the third subsystem. Actually, the list may coincide with the whole list of variables of the integrated model. Since the integrated model used for water quality planning contained several hundreds of variables, we had to restrict the list with two kinds of performance indicators:

1. investment indicators that included total cost of the project and investment at the territory of particular regions,
2. resulting concentration of pollutants in the regions as well as maximal concentration of pollutants in the river (in relative units, while the value of an indicator equals to one if the pollution level precisely satisfies the requirements of the medicine).

Any desirable restriction on the values of decision variables can be imposed, too. It is important, that application of the indicator list helps to involve users with different interests.

Secondly, a discussion of a selected strategy can be started at the same screening stage of the decision process. For this reason, selected decision strategies are displayed in a specially prepared GIS. Due to this, user can better understand the results of screening. Moreover, user can re-start the above processing of the integrated model by specifying new screening criteria and additional restrictions imposed on its variables. Decision makers and experts can use iterations of the decision screening process. Iteration starts with the specification of criteria and restrictions and is completed by exploration of a selected strategy. During the specification step, user can apply knowledge on the properties of the problem provided by decision maps and by map-based display of strategies selected on the previous iterations. Strategies can be stored in a database.

The DSS turned to be a convenient transparent tool for screening of strategies for water quality improvement. During one of the meetings at the Russian federal ministry for Natural Resources, the vice-minister in charge for internal water management, Mr. Mikheev had said that the DSS must be used for screening of water quality plans in all river basins in Russia. Unfortunately, this desire can not be satisfied easily since the problems of data preparation does exist.

It is important that the described technology can be applied on computer networks. FGM can be easily implemented on a network since approximation of the EPH, which is related to 99% of computing efforts of the technique, is separated from human exploration of decision maps. In addition, approximation of the EPH is performed automatically. Therefore it can be accomplished on a server while exploration can be executed by mean of Java applets on user's computer. A Web server equipped with the Java-based FGM software can be started. It can be used in the process of negotiation preparation by federal and regional authorities. However, it is even more important that millions of ordinary Internet users can be involved: they can apply such Web server individually to obtain information on the whole variety of possible strategies (in contrast to one or two strategies usually provided by mass media). Since the FGM technique is simple enough to be mastered by any computer-literate person, they will be able to screen the variety of possible strategies by themselves. To get an impression of this concept, one can try a Java-based educational resource (Lotov et al. 2000). Such Internet resources may help ordinary people to understand decision problems faced by authorities and to control public decision process actively.

Acknowledgment

This paper was partially supported by the Russian Foundation for Basic Research, grants No 98-01-00323 and No 00-15-96118.

References

Cohon, J. (1978): Multiobjective Programming and Planning. Academic Press, New York

Dorfman, R. (1965): Formal Models in the Design of Water Resource Systems. Water Resources Research 1(3), 329-336.

Gass, S., and Saaty, T. (1955): The computational algorithm for the parametric objective function. Naval Research Logistics Quarterly, 2, 39.

Lotov, A. V. (1994): Integrated Assessment of Environmental Problems. Computing Center of Russian Academy of Sciences, Moscow (Russian).

Lotov, A. (1996): Comment to the Paper by D. J. White “A Characterization of the Feasible Set of Objective Function Vectors in Linear Multiple Objective Problems”. European Journal of Operational Research 89(1), 215-220.

Lotov, A. (1998): Computer-based support for planning and negotiation on environmental rehabilitation of water resource systems. In: Loucks, D.P. (ed.) Rehabilitation of Degraded Rivers: Challenges, Issues and Experiences. Kluwer Academic Publishers, Dordrecht, 417-445.

Lotov, A., Bourmistrova, L., and Bushenkov, V. (1999a). Efficient strategies. An application in water quality planning. In: Kersten, G., Mikolajuk, Z., Rais, M., and Yeh, A. (eds.) Decision Analysis and Support for Sustainable Development. Kluwer Academic Publishers, Dordrecht, 145-166.

Lotov, A., Bushenkov, V., Chernov, A., and Kistanov, A. (2000): Experimental Internet Resource for Development of Independent Strategies. http://www.ccas.ru/mmes/mmeda/resource/

Lotov, A., Bushenkov, V., Chernov, A., Gusev, D., Kamenev, G. (1997): Internet, GIS, and Interactive decision maps. Journal of Geographical Information and Decision Analysis, v.1, No 2, 119-143; http://publish.uwo.ca/~malczew/gida.htm

Lotov, A. V., Bushenkov, V. A., Kamenev, G. K. (1999b). Feasible Goals Method. Edwin Mellen Press, Lewiston, NY USA (Russian)