Methodology and application of Pareto frontier visualization in DSS for the design of water quality improvement strategies in multi-regional river basins

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Abstract: The methodology and real-life application of a new graphic approach to the design of water quality improvement strategies in multi-regional river basins is described. The approach has two main features: (1) it applies a simplified integrated model developed on the basis of diverse data and mathematical models; and (2) it is based on interactive visualization of the Pareto (non-dominated, efficient) frontier in the process of multi-criteria screening of possible decision strategies. The approach is used in the DSS for the design of water quality improvement strategies in large multi-regional river basins. The integrated model used in the DSS consists of three models that describe: (1) wastewater discharge; (2) wastewater treatment; and (3) pollution transport. The first model is based on statistical data and expert estimation of the discharge in the regions located in the basin. The second model was developed on the basis of a database of wastewater treatment technologies. The third model describes the inter-regional pollution transport in the simplified form of influence matrices that were obtained through simulation of a detailed pollution transport model for several types of pollution. The integrated model was studied by the new graphic multi-criteria technique called the Interactive Decision Maps (IDM). The IDM technique helps to explore the Pareto frontier of the feasible criterion set in the case of three to seven decision criteria. The Pareto frontier is displayed in the form of multiple decision maps, which are collections of tradeoff curves for pairs of criteria. The decision maps are provided on-line and animated. Users are informed on feasible combinations of criterion values and on efficient criterion tradeoffs. Selecting of a water quality improvement strategy is based on identification of a feasible goal directly on display. Then, the associated strategy is computed and displayed by a GIS, which informs on spatial aspects of the strategy.

Keywords: environmental decision support; multi-criterion decision support; computer visualization; water management.

1. INTRODUCTION

This paper is devoted to a new graphic approach to supporting of environmental planning and its application in several water-related decision support systems (DSS). The approach is supposed to be used at the early screening phase of the decision procedures, which is aimed at the design of a small number of strategies that are a subject of further detailed exploration during the subsequent phase of final selection. The concept of the design phase of the decision process was introduced by Simon [1960]. Dorfman [1965] proposed some features of the design (screening) phase in the case of water-related problems. In particular, he stressed the use of simplified models. Indeed, since one cannot explore the whole lot of possible decision strategies in details, simplified models must be used at this phase. In addition, decision screening usually requires integration of models from a number of disciplines. For this reason, a simplified integrated mathematical model must be applied.

Water management (and especially environmental water management) is usually associated with conflicting interests. Even in the case of a single decision maker, conflicting decision criteria like cost, pollution indicators, etc., must be taken into account. Fairly often such decision making is related to a negotiation process that involves several (or even multiple) decision makers that represent different economic sectors and regions. It is clear that decision makers may have different interests and goals. Because of these features, the problems of water management usually result in multi-criteria formalization, which assumes involvement of human beings into the decision
process. Preferences of various decision makers (as well as other people involved) are used to settle balance between the criteria. To provide a simple computer support for all these people at the screening phase, we apply visualization of the Pareto (efficient, non-dominated) frontier of the variety of feasible criterion vectors. Such frontier describes limits of what is possible in terms of decision criteria and informs how an improvement of one particular criterion is related to losses in other criteria. In other words, the Pareto frontier informs on the criterion tradeoff. The idea to compute and display the Pareto frontier for two criteria was introduced by Gass and Saaty [1955] and transformed into a generic approach to environmental decision problems by Cohon [1978]. The Interactive Decision Maps (IDM) technique develops the idea for the case of multiple criteria (three to seven, and even more).

The screening phase of water planning can last for months and even years. Due to this, multiple stakeholders, independent institutions and political groups, as well as experts associated with them, may take part in screening activities. For this reason, computer procedures of decision screening must be transparent and simple. In particular, multiple questions concerning decision maker’s preferences must be avoided. Visualization of Pareto-efficient frontier provided by the Interactive Decision Maps (IDM) technique satisfies this requirement. Due to it, such graphic approach to screening problems turned out to be practical and was applied in several water management problems including water quality planning in large river basins.

The content of the paper is as follows. Section 2 outlines the preparation of integrated models. Application of the IDM technique in the DSS for water quality planning is given in Section 3. Section 4 outlines new developments including Internet-based applications.

2. INTEGRATION OF WATER-RELATED DECISION MODELS

A universal approach to constructing a simplified integrated model of a water-related system can be based on approximation of the input-output dependencies of its subsystem. If a mathematical description of a subsystem exists, a simplified model can be deducted from it. In the opposite case, expert judgments and empirical data may be used.

The most important and well-known example of such simplified models is provided by influence matrices, which are linear descriptions of the relations between input and output. An influence matrix can be constructed precisely in the case of a linear model. In the non-linear case, such a matrix describes the dependencies only approximately.

The DSS used in our studies use integrated models that include three simplified models:

1. The pollution transport model that computes pollutant concentrations at monitoring stations for given wastewater discharge. The model is composed of influence matrices (one matrix per a pollutant). The current DSS applies the modeling system MIKE 11 for constructing the matrices.

2. The wastewater discharge model that attributes the current discharge to particular regions, river segments and industries. It is based on corrected discharge reports received from the industrial enterprises and municipal authorities.

3. The wastewater treatment model that relates decrement of the wastewater discharge to cost. It applies the concept of wastewater purification technologies, which were described by experts.

An integrated model of an environmental system is given by a combination of influence matrices, balance equations, other descriptions and various constraints. Its decision variables describe the investment into particular purification technologies in particular regions and (or) industries.

3. APPLICATION OF IDM TECHNIQUE

The above approach was used in a series of water-related DSS developed in 90s on the request of Russian water managers (see Lotov et al. [1997], [1999] and [2001]). Two of them support the search for water quality improvement strategies in river basins. The first DSS is industry-oriented, and the second one describes regional aspects. We describe application of the IDM technique using an example related to the second DSS, which is calibrated now for the Oka River. The DSS has a tool for selecting of desired screening criteria from a large list. Due to this, people with various interests are able to use the DSS. Let us suppose that the user has selected three criteria:

1. maximal (in the river) concentration of nitrates ($Z_4$);
2. maximal (in the river) concentration of oil products ($Z_5$); and
3. cost of the project ($F$).

Concentrations are given in relative units (“one” is the value required by sanitation inspection), and cost is given in billions of US$. Let us start with the second and the third criteria. In Figure 1 the values of the pollution are given along the vertical axis and the values of cost are
given along the horizontal axis. Shaded area shows feasible combinations of cost and pollution. The points of the white area are not feasible. The Pareto frontier (tradeoff curve) given by the border of the areas displays the limits of what is feasible.

Figure 1. Feasible values of two criteria

By comparing two points of the frontier, the user obtains information on the additional payment related to a decrement of pollution. For example, concentration of oil products can be decreased substantially from its maximal value $Z_5 = 3.4$ till $Z_5 = 1.57$ for the cost of only $257.5$ million (see the cross). So, more than one half of the pollution vanishes only for 9% of the maximal investment, which is $2.8$ billion). Additional cost, however, is not so efficient: the slope of the frontier changes drastically in the vicinity of the cross. One can easily estimate that $Z_5 = 0.5$ requires $1.87$ billion, and the rest of investment (about $1$ billion!) is even less efficient. This example shows that a simple-minded minimization of the pollution level sometime results in wasting of money.

Figure 2. Decision map (black-and-white copy)

Now let us consider three criteria. In this case the user has to explore the decision map given in Figure 2. Here pollution concentrations are given along axes and the values of cost (from zero to one billion) are given by shading (color on display). Relation between cost and the shading are given in the palette under the graph. Let us consider the internal dark gray area related to the minimal (in Figure) cost of $0.3$ billion. Its frontier informs on limits of what is possible for this cost. One can see how one concentration can be exchanged for another. There is a kink on this frontier that displays a reasonable combination of pollutant concentrations for this cost. Other frontiers display information on the results related to higher values of cost. By comparing different frontiers, the user obtains knowledge about the influence of cost on feasible concentration of both pollutants, i.e. on tradeoffs for all three criteria.

Sliders of two scroll-bars located under the decision map provide the values of the fourth and fifth criteria. These criteria describe concentrations of the above pollutants in Moscow region. By moving the sliders, the user can change the criterion values. The decision map changes automatically. Moreover, animation (automatic movement of a slider) can be used. So, the user can explore the influence of the fourth and fifth criteria. Due to scroll-bars, influence of a larger number of criteria can be explored, too. In addition, matrices of decision maps related to several fixed values of the fourth and the fifth criteria can be displayed and animated. The user can request and explore the decision map for any group of criteria studying by this the conflicts between particular regions or industries.

To express his/her preferences, the user has to identify a preferred feasible combination of criterion values (feasible goal) directly on display by a click of the computer mouse. In contrast to the standard goal methods, the goal is feasible now. It means that there exists an investment strategy that results in the identified goal. That is why such method for decision screening is termed as the Feasible Goals Method (FGM). An efficient strategy associated with the feasible goal is computed automatically and displayed in a GIS.

One can see that the procedure of decision screening is fairly simple. The decision maps can be used for explanation of the reasons for identification of a particular feasible goal. Due to it, the selection of the goal is transparent. It is interesting that the users prefer to apply the evolutionary approach to the screening. Several steps of goal identification and exploration of the resulting strategy are used. Knowledge on feasible criterion values and on the strategies obtained on the previous steps helps to specify new criteria and explore new decision maps.

The IDM technique is based on the preliminary approximation of the so-called Edgeworth-Pareto Hull (EPH), which is composed of the points of the feasible criterion set and all dominated criterion points. The non-dominated frontier of the EPH coincides with the Pareto frontier. Due to this fact, frontiers of two-criterion slices of the EPH display tradeoff curves. After the EPH has been approximated, computing and display of thousands
of slices takes less than one second. This is basis of the on-line display of the decision maps and their animation. Since the approximating process is carried out automatically, the user does not need to trouble about it. The approximation methods are described in Lotov et al. [1999] and [2001].

The above two DSS are based on linear integrated models. However, the IDM technique can be used for exploration of non-linear models, too. To apply it, one has to consider any large finite number of decision alternatives and to compute criterion vectors associated with them. Then, the variety of computed criterion vectors (points) is enveloped and the EPH of the envelope is displayed by the IDM technique. An example of such application of the IDM technique for water quality planning in the non-linear case is given in Lotov et al. [2001]. Though it is related to water quality planning in a small part of a river, the approach can be used in the case of large river basins, too. Therefore, we provide here a black-and-white copy of the decision map that is used in the study (Figure 3). Here cost is given along the horizontal axis, and concentration of one of the pollutants is given along the vertical axis. Concentrations of another pollutant are given by color. The decision map displays the envelope of about 400 thousand strategies of water quality improvement. Note that the decision map does not look more complicated than decision maps for linear models. Identification of the goal is done in the same way, too. Enveloping of criterion points is the main idea of the Reasonable Goal Method (RGM) developed for visualization of databases including databases that contain outputs of non-linear models.

4. CONCLUSION

A new DSS for water quality planning in large river basins is under the development, which takes measures against pollution from non-point sources into account. Another new development is Internet application of the IDM technique. The basis of such application of the technique is provided by the fact that approximation of the EPH, which is related to 99% of the computing efforts, is performed automatically and is separated from the exploration of the decision maps. So, client-server scheme of interaction with a remote user is possible – computing is performed at a server while exploration of decision maps is carried out by means of Java applets on the user’s computer. Examples of such application are already available at http://www.ccas.ru/mmes/mmmeda/. Such tools can provide the basis of the democratic paradigm of environmental decision making. In contrast to the traditional technocratic (or expert-oriented) paradigm, the new paradigm tries to involve the non-experts into the process of decision making (see Lotov et al. [2001]).

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6. REFERENCES