ETLA ELINKEINOELÄMÄN TUTKIMUSLAITOS
THE RESEARCH INSTITUTE OF THE FINNISH ECONOMY
Lönnrotinkatu 4 B 00120 Helsinki Finland Tel. 601322 Telefax 601753

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V. Bushenkov** - V. Kaitala*** - A. Lotov** - M. Pohjola****

DECISION AND NEGOTIATION SUPPORT FOR TRANSBOUNDARY AIR POLLUTION CONTROL BETWEEN FINLAND, RUSSIA AND ESTONIA*

* This research is a part of the activities of the Russian-Finnish Technical Working Group on Operations Research. Copies of the computer program can be obtained from the authors upon request.

** Computing Center of the Russian Academy of Sciences, Russia

*** Systems Analysis Laboratory, Helsinki University of Technology, Finland

**** Helsinki School of Economics, Finland

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ABSTRACT: We present instrumental software for negotiation and decision support for transboundary air pollution abatement. Using this system the decision-maker can interact with a multiple criteria optimization model consisting of regional sulphur abatement cost functions and of a submodel describing the transportation of sulphur between Finland, Russia and Estonia. The PC program visualizes the Pareto-optimal set of chosen policy criteria which may include sulphur deposition rates and abatement costs in some or all of the countries. The program also computes and displays the optimal abatement policy corresponding to the Pareto-optimal (or other attainable) point specified by the decision-maker.

1 Introduction

Acid rain is one of the major environmental concerns in Europe (see, for example, Kauppi et al. 1990). It is known to render lakes incapable of supporting aquatic life, to threaten forest and agricultural productivity and to damage statues and other exposed materials. Airborne concentrations of sulfate particles can also increase morbidity rates, even premature mortality.

Sulphur and nitrogen oxides stay aloft for one to three days and are transported by the wind over distances ranging from 50 to 2000 kilometers. This fact makes the environmental problem transnational. Countries are both sources and victims of acid rain, which can thus be regarded as a regional reciprocal externality. Cooperation among the countries concerned is a natural solution to the problem. In fact, one approach in studying the economics of acid rain in to formulate it as an international multiperson decision-making problem (see, for example, Mäler 1990, Kaitala et al. 1991, 1992a,b).

A key issue in international cooperation on pollution control is the allocation of abatement resources among the countries involved. Where and how should these scarce resources be directed so as to maximize the net benefit from abatement reduction? As Mäler (1990) and Kaitala, Pohjola and Tahvonen (1991, 1992a,b) have demonstrated, cooperation may entail financial transfers from some countries to others. The need for such payments is a stark reality in international cooperation because there is no supernational authority with the power to enforce agreements. These game-theoretic studies are not, however, designed to analyze allocational questions as such but to reveal the benefits from cooperation (for an exception, see Tahvonen et al. 1992).

This paper concentrates on the allocational questions. We present instrumental software for decision and negotiation support on transboundary air pollution abatement. The main goal is to provide new opportunities for studying international acid rain problems and for specifying reasonable abatement strategies. The basis of the method is in characterizing the relevant alternatives in international environmental cooperation. These are displayed by the set of all attainable values of the chosen performance criteria, such as sulphur depositions and abatement costs in various regions, and by their trade-offs. The attainable set is constructed from the mathematical model describing the transportation of air pollutants between the countries and their regions.

The construction of the attainable set can be done by means of a new operations research method, the Generalized Reachable Sets (GRS) method, which is an analytical tool designed to support negotiations and decision-making. Two-dimensional slices of the attainable set can be displayed graphically and studied on the screen of a PC. The visual study of the possible alternatives, the trade-offs among the criteria, and the restrictions involved in the problem helps the analyst to evaluate the essential differencies between the alternatives. The decison-maker is asked to choose the best (from his or her own point of view) attainable combination of the specified performance criteria values. The computer program then constructs a feasible decision resulting in the "best" values of the criteria.

We use this this method to study acid rain in Finland, Russia and Estonia. In 1989 the governments of Finland and the Union of Soviet Socialist Republics signed an action plan for the purpose of limiting and reducing the deposition and harmful effects of air pollutants emanating from areas near their common border. The recent political events have made this agreement obsolete. Estonia, unlike Russia, does not recognize the agreements signed by the former Soviet Union. Finland has responded to the change in the international environment by seeking cooperation with the new independent nations. An agreement setting guidelines for bilateral cooperation with Estonia was signed in 1991. The government of Finland has also made a decision on a program of environmental aid to Eastern Europe. The plan is to support environmental investments in areas which are the sources of transboundary air pollutants deposited in Finland.

The method we have devised helps to solve this kind of problems. Negotiators, e.g. experts from Finland and Russia, can study the trade-offs between sulphur deposition rates as well as abatement costs in the individual countries. These are obtained from a sulphur transportation model and from estimated abatement cost functions. The method assists in choosing appropriate attainable combinations of the values of the chosen criteria and in obtaining corresponding abatement strategies.

The GRS approach has previously been used for various purposes: evaluation of the potentialities of economic systems (Lotov 1984a), multiple objective decision making (Lotov 1989) and investigation of the properties of dynamic models (Lotov 1972, 1975) etc. The GRS method has also been applied in investigating various regional economic systems taking into account environmental aspects (Bushenkov et al. 1982, Kamenev et al. 1986 and Lotov et al. 1991). See Lotov (1989) for detailed references.

The GRS method is described in greater detail in the next section. The sulphur transportation model and abatement cost data are given in section 3. The last section demonstrates how to use the program in environmental policy analysis.

2 The Generalized Reachable Sets method

Mathematical formulation of the GRS method for a static, linear finite-dimensional model is as follows. Let $x = (x_1, ..., x_n) \in R^n$ denote the vector of decision variables of the model. Let the mathematical model under study be

$$Ax \leq b, \tag{1}$$

where A is a given matrix and b is a given vector. The *feasible set* X is described in this case as follows

$$X = \{x : Ax \leq b\}. \tag{2}$$

Let y be an $m-$dimensional vector of criteria (objectives). Assume that it is connected with the decision variable x by the linear mapping given by the matrix F, i.e.,

$$y = Fx. \tag{3}$$

The *attainable set* (the feasible set in the criterion space or the Generalized Reachable Set) Y is defined as

$$Y = \{y : y = Fx, x \in X\} \tag{4}$$

or, for the set X described by (2), as

$$Y = \{y : y = Fx, Ax \leq b\}. \tag{5}$$

The GRS approach consists of approximating the set Y in the form

$$\{y : Dy \leq d\}, \tag{6}$$

where D is a matrix and d is a vector (to be calculated), and of further visual investigation of the set (6).

The attainable set Y contains full information about the possible outcomes of decisions if the outcome is described by the vector y. This information can be displayed to the decision makers (or any other persons concerned) by visualizations of two-dimensional cross-sections (slices) of Y on the computer screen in a dialogue mode. Since the set Y is constructed in the form (6) before the dialogue, a slice of Y or even a series of such slices can be obtained in a few seconds upon request. According to our experience, the capacity of displaying the slices is sufficient for obtaining a proper understanding of the form of the convex set Y in the objective space of three to six dimensions. For those models (1) which contain thousands of decision variables, Y can be constructed on a main-frame computer while the interface can be implemented on a personal computer. Note that once the set Y has been constructed, different persons can study it independently by obtaining different slices of it.

Let us suppose, in addition, that we are interested in maximizing the objective function values. In this case our interest is focused on the efficient (Pareto-optimal, non-dominated) points of the set Y , i.e., on the efficient set

$$P(Y) = \{y \in Y : (y' \geq y, y' \in Y) \Rightarrow y' = y\}. \tag{7}$$

The set $P(Y)$ constitutes a part of the boundary of Y. Therefore, by displaying slices of Y, one can obtain an understanding of the structure of the efficient set as well. One can also choose some points of interest in the efficient set. In this case the GRS method is similar to the methods that seek to generate the efficient set in the objective space (see Cohon 1978, Steuer 1986). The principal difference between our approach and the efficient set generating methods is the fact that we are approximating the attainable set (which is convex in many cases) instead of the efficient set (which is often non-convex).

As is usually done in methods of generating the efficient set, the decision maker is given complete freedom of choice with respect to the efficient points. Once the point in the objective space has been chosen, it is possible to obtain the decision which will lead to the chosen point. If the set Y is constructed approximately and also the efficient points are chosen approximately, the chosen point can be regarded as a "reference point" (see Wierzbicki 1980).

The described method of efficient set investigation has important advantages over well-known methods of displaying the efficient set via its points. First of all, it provides a clear visual representation of the efficient set and of the trade-offs between the criteria. Furthermore, the experts are studying slices of the set Y according to their own particular interests. These points are more appropriate for them than points obtained automatically, without taking their interests into account, as, for example, in the case of generating the entire set of the efficient vertices of Y (Zeleny 1974). It is important to recognize that the efficient set is often unstable with respect to small perturbations of the system coefficients, but the attainable set is usually stable (Lotov 1984b).

If we are only interested in the efficient set $P(Y)$, it is possible to construct the set

$$Y^* = \{y : y \leq Fx, x \in X\} \tag{8}$$

instead of Y. It is clear that Y^*, in addition to the points belonging to Y, also contains all the dominated points of the objective space. But efficient boundaries of both sets coincide, that is $P(Y^*) = P(Y)$. The structure of the boundary of Y^* is simpler than that of Y, and, consequently, easier to understand.

The idea to construct and visualize the efficient set for $m = 2$ was suggested by Gass and Saaty (1955). For this they used parametric linear optimization. An alternative method was introduced by Cohon (1978). The main difference of our approach amounts to the following: we study models with many objectives, i.e. $m > 2$, and we visualize the slices of Y^*, instead of $P(Y)$.[1]

The present mathematical description of the approach relates to static linear finite-dimensional models. Nevertheless, it can be easily reformulated for linear mathematical systems in linear functional spaces of the general type, involving ordinary differential equations and equations in partial derivatives. In these cases the feasible set and the mapping must be approximated by their finite-dimensional analogues.

3 Data and the model

In 1988 the Finnish-Soviet Commission for Environmental Protection established a joint programme for estimating the flux of air pollutants emitted close to the border between the countries. It consists of the estimation of emissions, model calculations of transboundary transport of pollutants, analysis of observational results from measurement stations and conclusions for emissions reductions. The emissions inventory includes sulphur, nitrogen and heavy metals.

Table 1 gives information about the depositions and emissions of sulphur in the relevant regions in the years 1980 and 1987. Depositions were calculated by Tuovinen, Kangas and Nordlund (1990) by applying the latest version of the long-range transport model for sulphur developed at the Western Meteorological Centre of the European Monitoring and Evaluation Programme (EMEP). Emission data approved by both the Finnish and Soviet parties were used as inputs in the model calculations. Finland is here divided into three subregions: Northern, Central and Southern Finland. To conform the analysis to the current political environment the

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[1] For more details on the construction of the attainable set, see Lotov (1972, 1975), Bushenkov and Lotov (1980), Bushenkov (1985), Chernykh (1988) and Lotov et al. (1992).

areas close to the eastern border of Finland are divided into two independent units: Russia and Estonia. The Russian areas are further split into three: Kola, Karelia and St Petersburg.

Both components of pollution are much higher in the Russian areas than in either Finland or Estonia. In 1987 the emissions of the nearby Russian regions were about three times larger than the Finnish. However, the trends are declining in all areas. In making comparisons between the regions it should be kept in mind that this Russian territory is about 25 percent larger than Finland and that Estonia is about the same size as Southern Finland. The annual sulphur depositions per square meter range from 0.5 – 0.6 grams in Northern and Central Finland as well as in Karelia to 1.2 – 1.3 grams in Southern Finland and Estonia.

The numbers in the parentheses in table 1 denote exogenous deposition, that is, deposition originating from emissions in other countries and the rest of Russia as well as deposition coming from unidentified (both natural and man-made) sources. About half of the total sulphur problem can be covered by the trilateral analysis.

Table 1: Sulphur emissions and depositions in 1980 and 1987
(1 000 tons per year)

	Emission E		Deposition Q			
	1980	1987	1980		1987	
Northern Finland	18	5	50	(27)	46	(26)
Central Finland	107	60	124	(66)	98	(59)
Southern Finland	167	97	89	(38)	66	(35)
Finland total	**292**	**162**	**263**	**(131)**	**210**	**(121)**
Kola	362	350	156	(36)	131	(27)
Karelia	85	85	118	(65)	95	(50)
St Petersburg	125	112	108	(57)	88	(46)
Russia total	**572**	**547**	**382**	**(158)**	**314**	**(123)**
Estonia	**120**	**104**	**71**	**(38)**	**60**	**(32)**

Source: Tuovinen, Kangas and Nordlund 1990

Tuovinen, Kangas and Nordlund (1990) have also estimated an annual sulphur budget between these seven regions for the year 1987. It can be used to formulate a sulphur transportation matrix indicating how the emission in one area is transported in the atmosphere for deposition in another. The columns of table 2 specify the deposition distribution between the regions of one unit of sulphur emitted in each area. The large numbers on the diagonal show how important own sources of pollution are for each region. The column and row sums are not equal to unity because all areas both emit sulphur to and receive it from the rest of the world.

Table 2: Sulphur transportation matrix for the year 1987

	Emitting region:						
	NFin	CFin	SFin	Kol	Kar	SPb	Est
Receiving region:							
Northern Finland	.200	.017	.010	.046	.012	.000	.000
Central Finland	.000	.300	.062	.011	.047	.036	.029
Southern Finland	.000	.017	.227	.003	.000	.027	.038
Kola	.000	.017	.000	.286	.023	.009	.000
Karelia	.000	.033	.031	.017	.318	.045	.019
St Petersburg	.000	.017	.031	.003	.012	.268	.058
Estonia	.000	.000	.031	.000	.000	.018	.221

Source: Tuovinen, Kangas and Nordlund 1990

A sulphur transportation model can now be constructed on the basis of tables 1 and 2. Let E_i and Q_i denote the annual emission and deposition of sulphur, respectively, in region i, and let A stand for the matrix of table 2 and B for the vector of exogenous deposition in 1987 as specified in the last column of table 1. The model can then be expressed in vector notation as

$$Q = AE + B. \tag{9}$$

To apply this model to the analysis of cooperation on transboundary air pollution between the three countries we need information about both future emissions and sulphur abatement costs. Table 3 contains estimates for the emissions in the year

2000 provided by the Finnish Integrated Acidification Assesment model (HAKOMA) (see Johansson et al. 1991). The Finnish estimates have been calculated by using the basic energy use scenario of the Ministry of Trade and Industry. The Russian and Estonian emissions are assumed to stay at their 1987 levels, as no other information is available.

Table 3: Estimated unabated sulphur emissions and depositions for the year 2000 (1 000 tons per year)

	Emission E	Deposition Q	
Northern Finland	7	39	(18)
Central Finland	90	93	(43)
Southern Finland	127	63	(25)
Finland total	**225**	**195**	**(86)**
Kola	350	129	(24)
Karelia	85	89	(42)
St Petersburg	112	83	(37)
Russia total	**547**	**301**	**(103)**
Estonia	**104**	**54**	**(25)**

Source: Johansson, Tähtinen, Amann 1991

Table 3 also contains our estimates for sulphur depositions obtained from model (9) by using the estimated emissions and by assuming that the man-made sulphur deposition originating from the rest of the world will be 50 percent lower that in 1980. We justify this assumption by referring to the Helsinki protocol of the Convention on Long-Range Transboundary Air Pollution according to which the 21 signatories will reduce their sulphur emissions by 30 percent from the 1980 levels. Moreover, about half of these countries have declared more ambitious cuts ranging from 40 to 80 percent.

The sulphur abatement cost function for the ith subregion is defined as the minimal cost envelope encompassing the entire range of sulphur abatement options for region i in a given time period. The costs can be calculated for various sulphur reduction requirements ranging up to the maximal technologically feasible removal. The HAKOMA project at the Tehnical Research Centre of Finland has derived such cost functions for Finland and the nearby regions (Johansson et al. 1991). These piecewise linear functions (see figure 1) are used in the software for illustrative purposes but other cost estimates can also be applied easily. The annual costs, measured in millions of Finnish marks, have been estimated on the basis of expected emissions for the year 2000 (table 3), and they include both capital and operating costs.

Given the sulphur transportation model and the cost functions, let us next consider possible criteria for optimization. The following main criteria can be chosen in the current software implementation:

a. sulphur abatement cost in each subregion;

b. abatement cost in Finland, in the nearby region of Russia, and in Estonia;

c. total abatement cost for the whole territory;

d. average sulphur deposition in each subregion;

e. maximal average depositions in the subregions of Finland, Russia, and Estonia;

f. maximal average depositions in the whole territory.

Sulphur deposition damages, estimated by Kaitala, Pohjola and Tahvonen (1991), can be used as additional criteria.

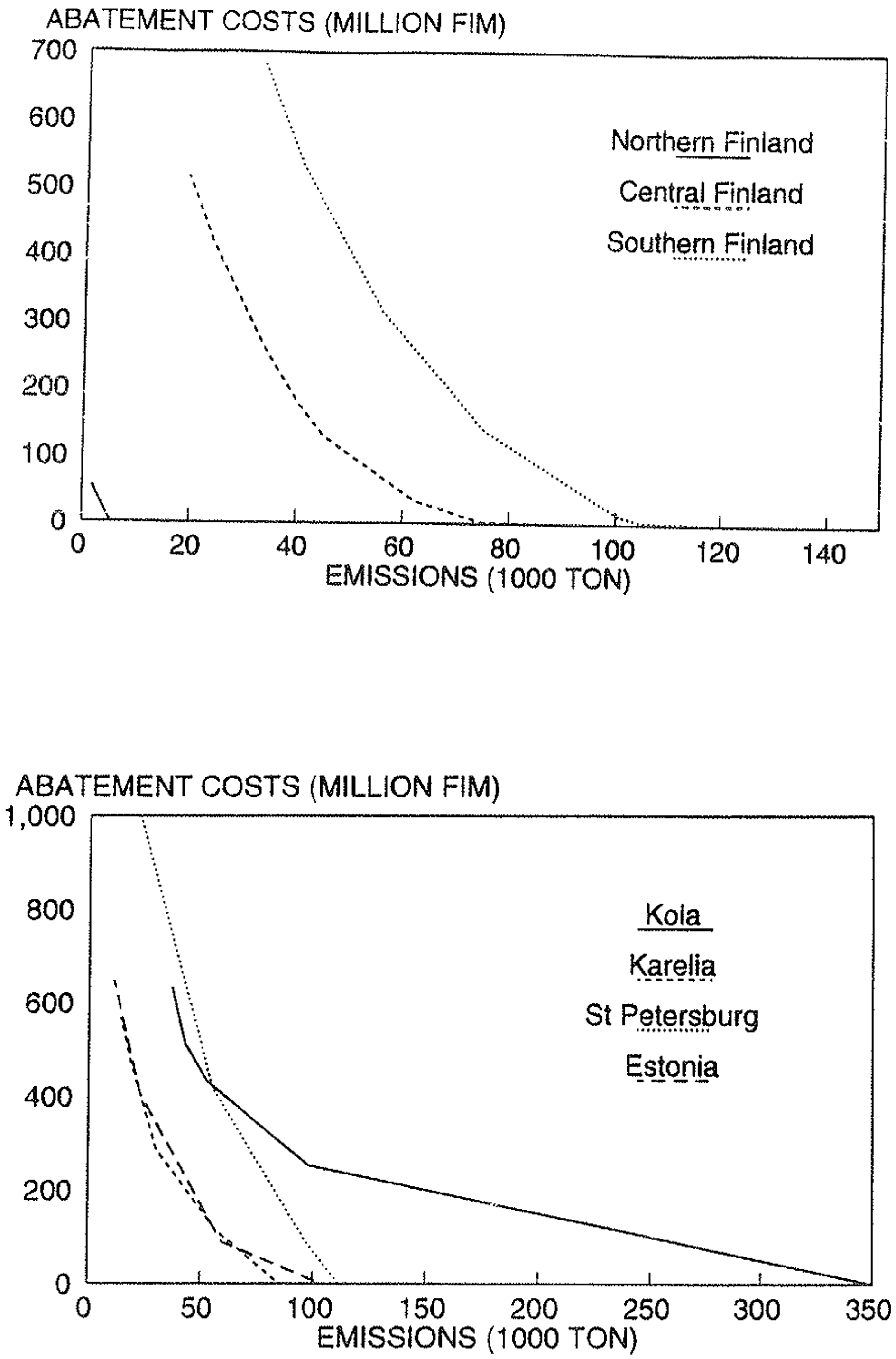

Figure 1: Sulphur abatement cost functions

4 Analysing a transboundary acid rain problem - an example

4.1 Using the software

Using the decision support system, based on the GRS method, includes the following main stages[2]:

1) problem formulation (defining the criteria and restrictions);
2) compatibility check of restrictions;
3) construction of the attainable set;
4) visual exploration of the attainable set by slices;
5) choice of particular solution points;
6) efficient decision construction;
7) decision display.

The researcher begins by choosing **emission abatement cost criteria**. The criterion set includes

1. abatement costs in any subregion;
2. abatement costs in the countries and
3. abatement cost for the whole territory.

Then the researcher defines **deposition restrictions.** Values can be chosen for the maximum rate (in grams per square meter) of sulphur deposition in any subregion, country or the whole territory.

One can also choose **damage criteria** in the same way.

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[2] For detailed instructions, see the Appendix

The direction of criterion improvement should be indicated as well. This information will be used in constructing efficient (Pareto-optimal) decisions on the sixth stage of the procedure. Initially, it is supposed that the decision-maker is interested in minimizing the criteria values, but it is also possible to assume the opposite type of behaviour. It may sometimes be the case that the decision-maker is indifferent as to the value of a particular criterion. This situation can be specified as well.

Restrictions on the values of the criteria can be imposed. The initial values of pollution deposition have been restricted from above by the values corresponding to the forecast for the year 2 000 given in table 3. Since these values are treated in the model as the pollution depositions corresponding to zero cost, these restrictions cannot be violated by any feasible decision. Thus, these values have been included to inform the researcher only. All other initial restrictions imposed on the performance criteria values have been chosen to satisfy any feasible decision and can be freely changed.

After the criteria have been chosen and the restrictions specified, the program checks the **compatibility of the restrictions.** If the restrictions are not compatible, the researcher has to redefine them. If they are compatible, then one can construct the attainable set and proceed to studying the solutions.

The visual exploration of the attainable set is based on displaying two dimensional slices of this set and on the choice of the preferred point on one of the slices. Afterwards, the efficient decision is computed automatically.

Any decision candidate obtained on the screen can be studied in more detail by displaying it as a TABLE, DIAGRAM, or HISTOGRAM. The decisions obtained can likewise be stored in an ASCII file and printed out.

4.2 Example

A simple example of the software application is described herein. Let us choose three criteria:

C1. abatement cost in Finland;

C2. abatement cost in the whole territory;

C3. maximum deposition rate in Finland.

It is assumed by the software that the decrement of all three criteria values are preferable. It should be noted that this problem formulation does not specify who will pay all the costs.

Let us impose the following restrictions:

R1. the deposition rate in the Northern Finland should not be greater than 0.4 gm^{-2}. (Note that the model predicts it to be 0.39 gm^{-2} in the year 2000, as shown on the screen);

R2. the deposition rate in the Central Finland should not be greater than 0.5 gm^{-2} (0.547 gm^{-2} in 2000).

The restrictions are compatible, and the Pareto-optimal attainable set can now be constructed and visualized. The range of total abatement costs in the whole region is between 0.02 and 4.1 billion FIM, as can be seen when the slices of the attainable set are drawn. We fix the following total cost values in order to study them in more detail: 0.25, 0.5, 0.75, 1.00, 1.25, 1.50, 1.75, and 2.00 billion FIM. The feasible solutions corresponding to these emission abatement cost values are illustrated by the eight slices in figure 2, in which the x-axis gives the total costs invested in Finland and the y-axis gives the maximum deposition rate in Finland. Slice 0.5 of the attainable set, which corresponds to the total cost of 500 million FIM, has the following properties. Choosing point A means that the 140 million of the total costs of 500 million will be invested in Finland. As a consequence the maximum deposition rate in Finland is 0.91 gm^{-2}. Increasing the Finnish share of the total costs (points B and C) yields a better result for Finland since the depositon rate decreases. However, increasing this share from, say, 410 million FIM (point C) to 500 million (point D) does not yield a better result. This means that, given the total amount of 500 million, all investments exceeding 410 (point C) give better results when invested somewhere else.

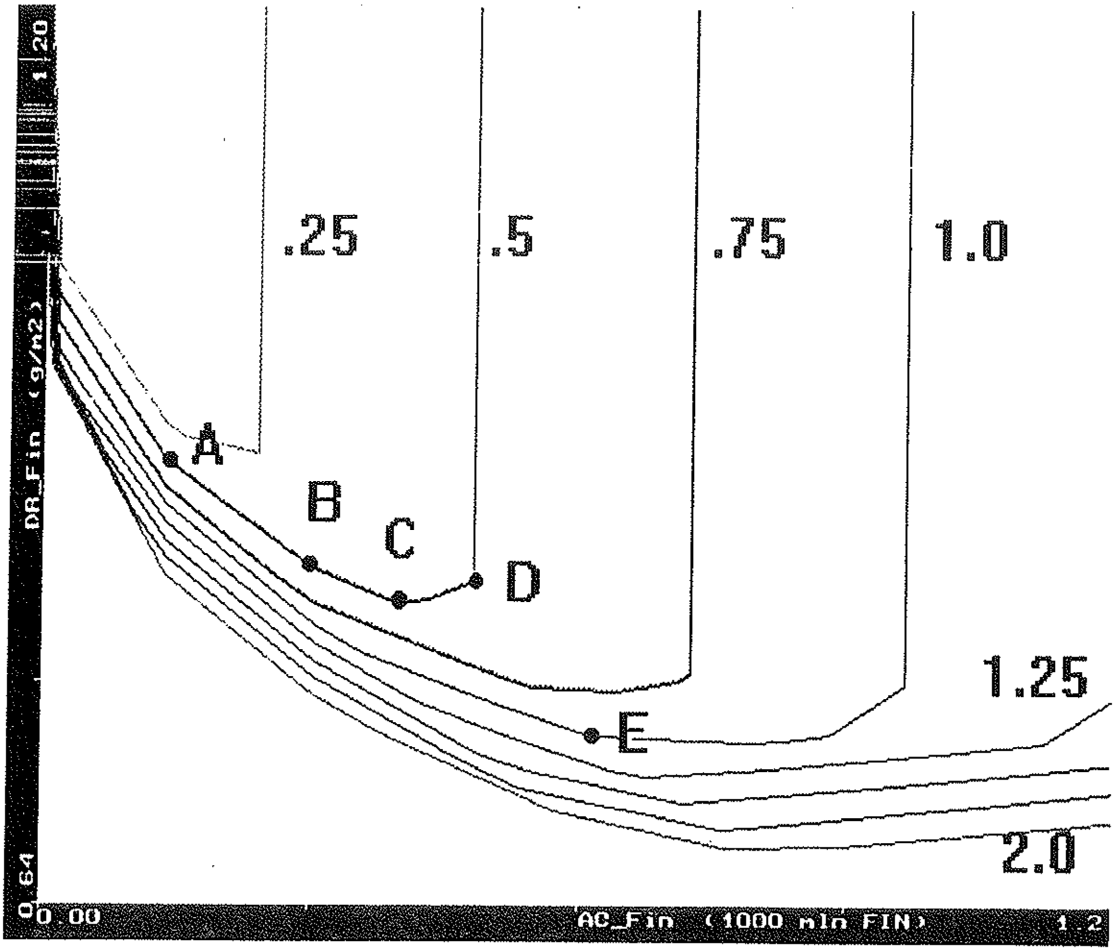
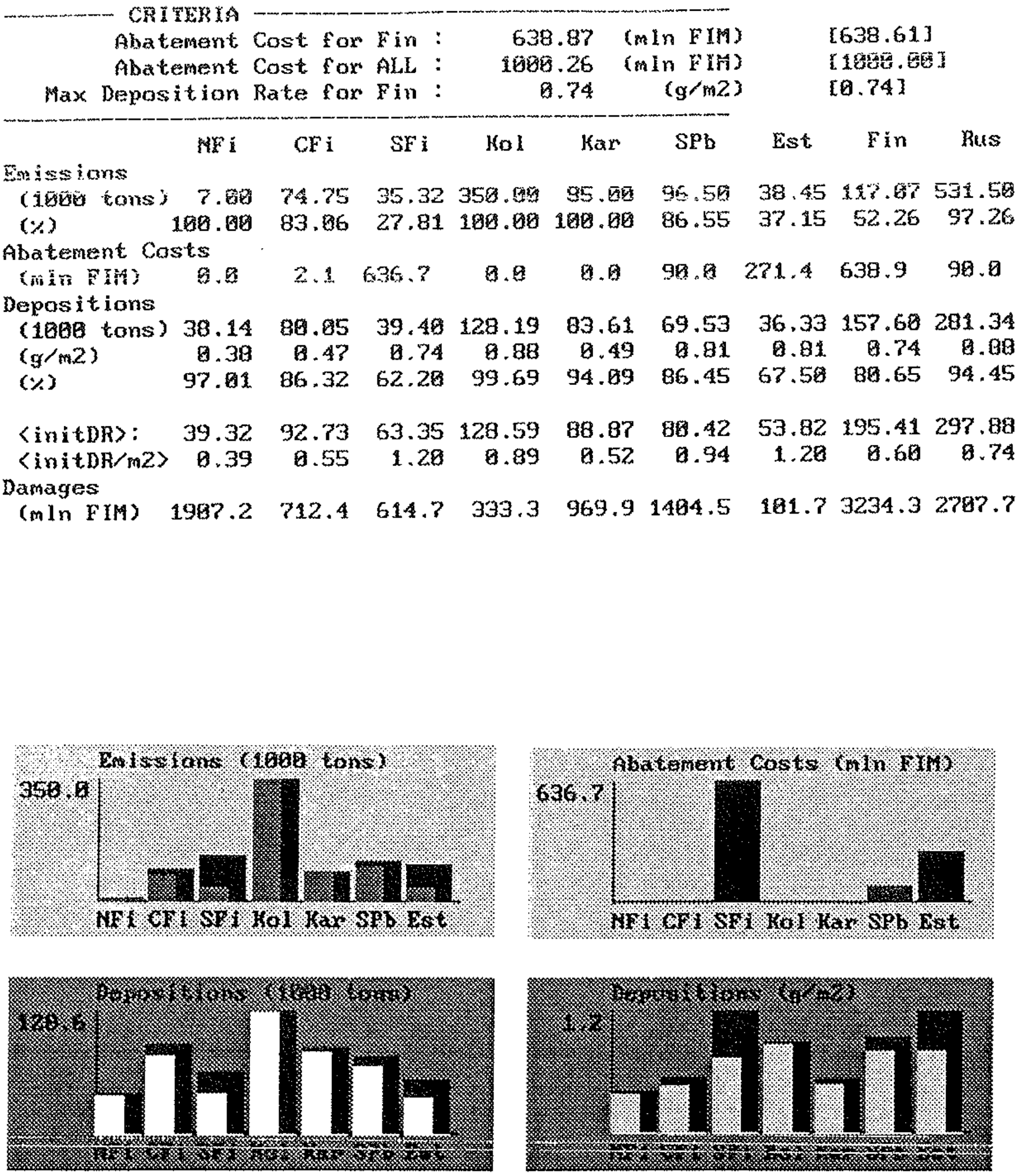


Figure 2: Visual exploration of the attainable set on the computer screen

Assume next that the total abatement costs are 1 000 million FIM. It is reasonable to choose point E on this slice since increasing the Finnish share of the total costs beyond this point does not reduce the maximum deposition rate in Finland. At this point the abatement costs in Finland are 640 million and the maximum deposition rate is 0.74 gm^{-2}. Thus, 360 million FIM are invested in the neighboring regions. Assume that the decision-maker chooses this point. The computer program solves the optimal abatement policies and their consequences. The emissions, abatement costs, depositions per square meter, and total depositions for Northern Finland (NFi), Central Finland (CFi), Southern Finland (SFi), Kola (Kol), Karelia (Kar), St. Petersburg (SPb), and Estonia (Est) are given in the table and histograms of figure 3. The data for the initial year (corresponding to zero abatement costs) are given by black columns. Decisions obtained are given as grey columns.

The optimal policy consists of abating sulphur mainly in Southern Finland, St. Petersburg and Estonia. Depositions will be reduced in all except the northernmost areas. Significant reductions are achieved in Southern Finland, Estonia and St. Petersburg. Perhaps the most surprising result in this case is that the emission and depositions in the Kola region will remain unchanged. This conclusion may, however, change if the exogenous sulphur deposition in Northern Finland is assumed to be higher than specified in our example.

The conclusion to be drawn from this case study is the fact that abatement investments should be directed to Finland when the amount of money to be used is rather modest. But when the decision-maker is willing to invest more, investments should also be directed to the neighboring regions. The investment share of these areas increases as the total investments rise.



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-------- CRITERIA ------------------------------------------
        Abatement Cost for Fin :     638.87  (mln FIM)      [638.61]
        Abatement Cost for ALL :    1000.26  (mln FIM)      [1000.00]
   Max Deposition Rate for Fin :       0.74     (g/m2)      [0.74]
------------------------------------------------------------
                 NFi     CFi     SFi     Kol     Kar     SPb     Est     Fin     Rus
Emissions
 (1000 tons)   7.00   74.75   35.32  350.00   95.00   96.50   38.45  117.07  531.50
 (%)         100.00   83.06   27.81  100.00  100.00   86.55   37.15   52.26   97.26
Abatement Costs
 (mln FIM)      0.0     2.1   636.7     0.0     0.0    90.0   271.4   638.9    90.0
Depositions
 (1000 tons)  38.14   80.05   39.40  128.19   83.61   69.53   36.33  157.60  281.34
 (g/m2)        0.38    0.47    0.74    0.88    0.49    0.81    0.81    0.74    0.00
 (%)          97.01   86.32   62.20   99.69   94.09   86.45   67.50   80.65   94.45

 <initDR>:    39.32   92.73   63.35  128.59   88.87   80.42   53.82  195.41  297.88
 <initDR/m2>   0.39    0.55    1.20    0.89    0.52    0.94    1.20    0.60    0.74
Damages
 (mln FIM)   1907.2   712.4   614.7   333.3   969.9  1404.5   101.7  3234.3  2707.7
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Figure 3: An example of the display of optimal policies

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Appendix: Instructions for using the software

The procedure includes seven main stages.

Stage 1) Problem formulation (defining the criteria and restrictions);

The researcher begins by choosing the criteria to be studied. After entering the system the MODEL CONFIGURATION item of the main menu is chosen. The researcher then chooses the CRITERIA item of the MODEL CONFIGURATING menu, after which a list of possible criteria (performance criteria) is displayed. It includes abatement costs in any region presented in the model, the abatement cost in the countries and abatement cost for the territory under discussion. The pollution deposition rate for any region, maximal deposition rate for the regions of any country and maximal deposition rate for the countries are presented as well. Using the **PgDn** key one can go on to choose criteria describing pollution damage.

When choosing this item for the first time, two criteria have already been chosen by the program: the overall cost and the maximal deposition rate in the countries under consideration. The researcher can walk through the menu using up and down arrows. The choice of the criterion can be done by using the **F2** key. The exclusion of the criterion chosen earlier can be done using the same key.

Remark 1. The total number of the criteria chosen is not supposed to exceed five or six.

There is a minus sign in front of the selected criterion. This means that during the computation of the efficient (Pareto-optimal) decisions it is assumed that the researcher is interested in decreasing the values of the criteria. Using the **F5** key it is possible to replace the minus sign by the *plus sign* or by the *point sign*. The plus sign means that an increment in this criterion is preferred, and the point sign means that the researcher is indifferent to changes in the related criterion value.

Restrictions on the criteria values can be imposed. To do this the researcher has to choose the desirable indicator and to use the **F3** key in the case of the lower limit and **F4** for the upper limit. The desired number should be entered into the window displayed.

At the start of the procedure the values of pollution deposition have been restricted from above by the values corresponding to the base year. Since these values are treated in the model as the pollution depositions corresponding to zero cost, these restrictions cannot be violated by any feasible decision. It means that these values have been presented to inform the researcher only. All other restrictions imposed on the performance criteria values at the start of the procedure have been chosen to satisfy any feasible decision.

Remark 2. During the procedure of choosing criteria it is important to remember that the attainable set (GRS) should not belong to any plane of the criterion space. This fact results in an important principle of criteria choice: the criteria should be linearily independent.

Assume, for example, that the abatement costs in the Northern, Southern and Central Finland as well as the total abatement cost in Finland will be used as cost criteria. Since the last criterion is the the sum of the first three, the criteria are linearily dependent. The construction of the attainable set fails in this case. For the same reason it is impossible to choose pollution costs and damage costs for any region simultaneously.

Remark 3. The range between the minimum and maximum criterion values should not be too narrow.

For example, if the abatement cost in Estonia is restricted both from above by 100 million FIM and from below by nearly the same value, then the attainable set may be unstable.

Stage 2) Compatibility check of the restrictions

After finishing the criterion choice and restriction imposition procedure, the researcher has to leave the CRITERIA item using the **ESC** key. He will automatically be brought to the COMPATIBILITY item of Problem Formulation menu. If the restrictions are not compatible, the researcher has to return to the CRITERIA item and to revise the restrictions. If the restrictions are compatible, the researcher returns to the main menu.

Stage 3) Construction of the Generalized Reachable Set (the attainable set)

The program brings the researcher automatically to the GRS CONSTRUCTION item of the main menu. After entering it the program starts to approximate the GRS. One can observe the process before it is stopped by the program. The starting time, the performance time and the distance between the internal and the external approximating polyhedrons are given.

Stage 4) Visual exploration of the attainable set by slices

and

Stage 5) Choice of the criterion values

After finishing the GRS approximation the researcher is brought to the GRS VISUALIZATION item of the main menu. He now enters the VISAN subsystem which helps to explore the attainable set by its slices and to choose values for the performance criteria.

Entering the VISual ANalysis system provides an opportunity to explore the attainable set which has been constructed in the previous step. The VISAN subsystem displays the attainable set in the form of two-dimensional cross-sections (slices) of the attainable set. After entering the VISAN subsystem you see the main screen which is divided into three fields: the menu field, the drawing field and the message field. The message field is the field for system messages and for input when necessary. The drawing field is for displaying slices. The menu field contains the main menu. The current menu item is highlighted. To move around the menu use up and down arrow keys. To enter the current menu item press ENTER.

Although you can obtain information on the highlighted menu item by pressing **F1**, we describe here the most important features of the VISAN system. The principle menu items are SLICES, TOPS, and POINTS. The SLICES item provides the opportunity to obtain two dimensional slices of the attainable set on display. It is possible to obtain packages consisting of up to 10 slices. The instructions describing the procedure of producing slices can be obtained by pressing **F1** when the SLICES item is selected. When the slices have been drawn, you can study them more carefully by using the TOPS item of the main menu. An arrow, which is the main feature of this item, points out the tops of the slices. The values of the tops are depicted in the menu field. It is possible to move the arrow along the boundary of any slice and to change for the next slice. Detailed instructions can be obtained by pressing **F1** when the TOPS item is selected. The POINTS item provides the opportunity to choose the most appropriate criterion point. You can use slices which you have studied earlier or can construct new ones. The decision resulting in the chosen point will be computed automatically after you leave the VISAN system. Detailed instructions for the choice of the preferred point can be obtained by pressing **F1** when the POINTS item is selected. Note that if you have chosen a dominated criterion point your decision will be automatically improved upon.

Stage 6) Efficient decision construction

After quitting the VISAN subsystem one has to wait until the efficient decision is constructed. The performance time of the process is presented on the display. Any chosen criterion point which is not efficient is corrected and the efficient criterion point is displayed after its construction has been finished.

Stage 7) Efficient decision display

Returning to the main menu the researcher is brought to the DECISION DISPLAY item. The decision can be displayed in three forms: TABLE, DIAGRAM, and HISTOGRAM.

The researcher is advised to go through them. The decision obtained can be stored in an ASCII file named by the user. The decisions obtained during a session can be then printed out.

Remark 4. The program can sometimes stop during the process of the GRS construction or efficient decision computation. This fact is indicated by the clock displayed during the process. It means that the RAM has been fragmented on the previous steps of the procedure. In this case the operation system must be reloaded (reboot) and the program must be restarted.

ELINKEINOELÄMÄN TUTKIMUSLAITOS (ETLA)
THE RESEARCH INSTITUTE OF THE FINNISH ECONOMY
LÖNNROTINKATU 4 B, SF-00120 HELSINKI

Puh./Tel. (90) 609 900 Telefax (90) 601 753
Int. 358-0-609 900 Int. 358-0-601 753

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