Chapter 2. Illustrative applications

Several illustrative applications of the FGM/IDM technique are considered in this Chapter. They show how the technique could be applied in various environmental decision problems. First we describe the search for efficient ocean waste disposal strategies based on the example of the New York Bight. In Section 2.2, the technique is applied in the process of searching for efficient strategies of regional agricultural development with groundwater level and pollution taken into account. Section 2.3 is devoted to exploration of long-term development of a national economy. In addition to economic growth, pollution and unemployment are considered. Section 2.4 describes the software tool that supports searching for efficient regional strategies for trans-boundary air pollution abatement. Section 2.5 outlines an approach to development of efficient strategies aimed at the abatement of the global climate change.

Simplified mathematical models of environmental systems are used in the studies. The simplified models are usually based on integration of simplified descriptions of sub-systems of the environmental systems. The methods for constructing such models are outlined in the next Chapter where they are exemplified by a process of developing a simplified integrated model that describes a real-life environmental problem.

2.1. Ocean Waste Management Decisions

In this Section we illustrate the FGM/IDM technique by an ocean waste disposal example, requiring difficult decisions concerning cost and resulting pollution. We reconsider the old problem of choosing sewage sludge disposal sites in the New York Bight. The Section is based on the paper (Lotov et al., 1998).

Sewage Sludge Disposal Problem

Contamination of the New York Bight has been a concern of the USA Environmental Protection Agency (EPA), and the neighboring municipalities for many years (see Figure 2.1.1). Concern for water quality in the Bight region is long standing, particularly for waters in the inner portion of the Bight. Highly publicized pollution-related episodes that have occurred over the past decades have had a lasting impact on public opinion. Being concerned about the contamination of the inner Bight region, in 1985 the EPA ordered New York City and the remaining users of the inner Bight region to begin shifting their dumping operations to the 106-mile site. In this study we reexamine, following Wallenius et al. (1987) and Leschine et al. (1992), the EPA decision in a way, which permits simultaneous multiple-site dumping.

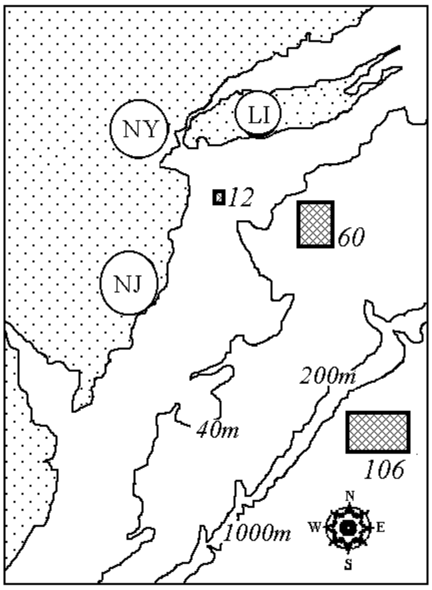


Figure 2.1.1. Map of the New York Bight region

Three alternative disposal sites were considered in the model: the 12-mile site, the 60-mile site, and the 106-mile site. We assumed that a combination of the above sites was a possibility, such that all three sites could be used at the same time in different portions. In the model all sludge was assumed to be produced in New York City, NY, (where 52% is produced), New Jersey, NJ, (41%), and Long Island, LI, (7%). Production of sludge was assumed to be constant from year to year. Two types of vessels were used for the transportation of the sludge: towed barges, and self-propelled barges. The constraint set of the model contained four parts:

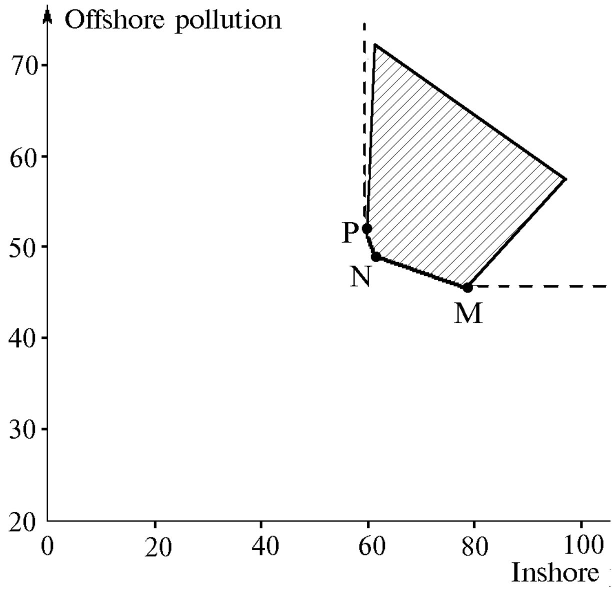


Figure 2.1.2. The variety of feasible criterion vectors and its EPH

1) constraints to ensure dumping of all generated sludge;

2) constraints of annual dumping capacity of barges;

3) constraints of amount dumped at each site;

4) constraints related to the ocean's assimilative capacity.

The following three criteria were used to evaluate different sludge disposal strategies:

- total cost of sludge disposal operation (in million of US$);
- pollution level at inshore monitoring station (pollution concentration, in percent to a given value);
- pollution level at offshore monitoring station (pollution concentration, in percent to a given value).

The decision variables included the number of self-propelled/towed barge trips from source (NY, NJ, LI) to site (12-, 60-, 106-mile sites). A formal description of the model is given in Leschine et al. (1992).

Application of FGM/IDM technique

To begin with, let us fix the total cost. Then all feasible values of inshore pollution and of offshore pollution are given by the variety of feasible criterion vectors on the criterion plane (see Figure 2.1.2 where the variety is shaded). The frontier of its EPH is depicted by a dashed line. As usually, the variety of feasible criterion vectors and its EPH have the same non-dominated frontier.

Since it is preferable for users to decrease both inshore and offshore pollution, we are interested in its "south-western" frontier, which is the non-dominated frontier. In the vicinity of point ***M***, a small decrement in the offshore pollution requires a substantial increment in the inshore pollution. Vice versa, in the vicinity of point ***P***, just a small rise in the inshore pollution results in a sharp decrement in offshore pollution. So, the form of the non-dominated frontier shows the how the offshore pollution is transformed into the inshore pollution if the efficient strategies are used. In other words, the non-dominated frontier informs user about the criterion tradeoff between inshore and offshore pollution.

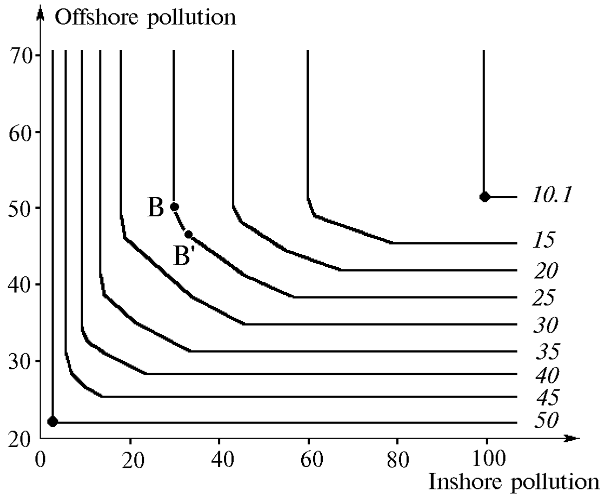


Figure 2.1.3. A decision map for several fixed costs

Decision map in Figure 2.1.3 is constructed as collections of two dimensional slices of the EPH, where several non-dominated frontiers between inshore and offshore pollution related to different values of total cost are given. With the help of the decision map, one can easily understand the relation between an increment in the total cost and the improvement of the environment (i.e., a reduction in the inshore and/or the offshore pollution). One can easily obtain different decision maps displaying the non-dominated frontiers "inshore pollution versus cost" and "offshore pollution versus cost".

Let us take a closer look at Figure 2.1.3. The cost is changing from the minimal US $10.1 million to the maximal US $50 million.

The non-dominated frontiers in Figure 2.1.3 are drawn with heavy lines. They have the following important feature: there is a conflict between inshore and offshore pollution, except for the $10.1 million and $50 million frontiers, which consist of just one point. It is important that the transformation rate (tradeoff) changes in process of moving along the non-dominated frontiers, and it depends on cost, too.

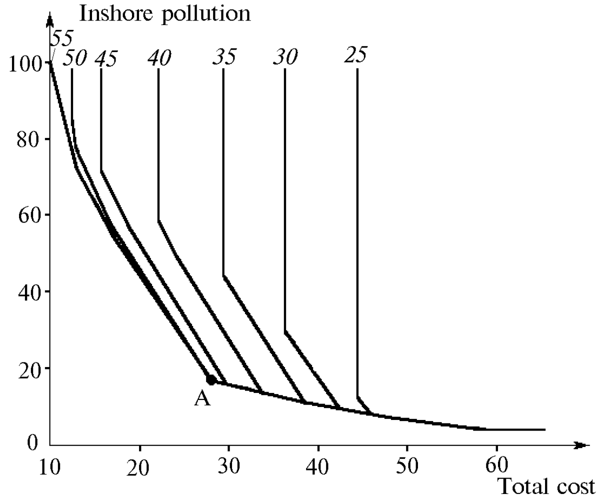


Figure 2.1.4: Cost versus inshore pollution

Let us compare the distances between pairs of non-dominated frontiers related to different costs. The $10.1 million and $15 million frontiers are quite apart, while the distance between the $15 million and $20 million frontiers is obviously smaller. This means that the extra $5 million investment has much more impact if the cost equals $10.1 million rather than $15 million.

The above phenomenon is explored from another angle of view in Figure 2.1.4 where an alternative decision map is displayed. The “cost versus inshore pollution” frontiers are given for several values of offshore pollution, ranging from 25% to 55% of its maximum value. One can see that every frontier contains a kink where the tradeoff between inshore pollution and cost changes drastically. If the offshore pollution equals to 55%, the kink occurs at point ***A***. Note that point ***A*** also belongs to another frontier that corresponds to 50% offshore pollution.

Figure 2.1.5 provides a zoomed part of the “inshore pollution versus total cost” frontiers, when the values of offshore pollution vary between 43% and 55%.

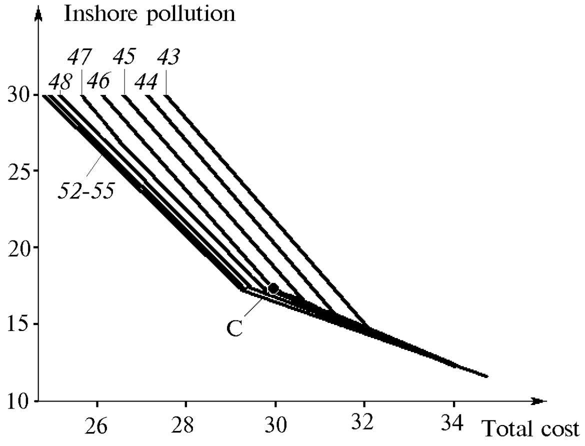


Figure 2.1.5. Cost versus inshore pollution with the goal point ***C***

It is interesting to note that if the offshore pollution exceeds 46%, further growth in it is practically useless: additional offshore pollution moves the frontier only marginally downwards. For this reason, the following feasible goal (point ***C***) may be of interest:

- cost equals to \$30 million,
- inshore pollution equals to 17.5%,
- offshore pollution equals to 46%.

Suppose the goal point ***C*** has been chosen as the decision maker's most preferred point. The associated decision provided by the computer is the following: transport all the waste to the 60-mile site. Strategies associated with other points of the non-dominated frontier could be found as well.

2.2. Search for efficient strategies of regional agricultural development taking groundwater level and water pollution into account

The results of a study carried out at the International Institute for Applied Systems Analysis (IIASA) in the middle of 80s is described in this Section. The study has been performed in the framework of the project "Regional water management strategies" headed by Dr. S. Orlovsky. The research was based on the experience obtained in the process of application of the FGM/IDM technique in the regional study described in Chapter 1. However, this time a real-life region was considered. This Section is based on the paper (Kamenev et al., 1986).

Introduction

The Southern Peel Region in the Netherlands was studied. The region has intensive agricultural production, which includes both crop and livestock. Future agricultural development of the region may result in negative environmental consequences. The problem is related mainly to the livestock production, which results in animal slurries as by-products. Animal slurries can be used for fertilization. To do it, slurries produced during the summer and the winter must be temporarily stored in tanks till the next spring and only then applied to the land. However, the storage is restricted by storage capacities, and for this reason a part of slurries may be stored outside of the tanks. In turn, this may result in groundwater pollution. Intensive application of animal slurries for fertilization may have the same result. Groundwater pollution may have not only environmental negative consequences, but negative consequences in the field of population health, too. It is related to the fact that local population uses the water from deep aquifers. Water quantity problems may arise, too: groundwater level is very important in several natural zones located in the region.

Model

We used an aggregated version of the model of the water resources and agricultural production in the region developed by Orlovski and van Walsum (1984). The Orlovsky-van Walsum model (OW model) linked submodels of agricultural production, water quantity and quality processes and soil nitrogen processes. Southern Peel region was divided into 31 subregions. The division was based on classes of groundwater conditions and soil physical units. In the framework of the OW model, a year was split into two parts:

- "summer" which starts on April 1, and
- "winter" which starts on October 1.

The year is taken from the beginning of winter.

For any region the groundwater levels in the beginning and at the end of the summer were considered. A model that relates deviations of the groundwater levels from their natural levels to water supply extractions was developed by means of linear parameterization of a complicated model of ground water flow developed in the Netherlands. Influence of water extractions in particular sub-regions on groundwater levels in all subregions was described on the basis of two influence matrices: winter influence matrix and summer influence matrix. The influence matrices constructed in simulation experiments carried out in the Netherlands (see Orlovski and van Walsum, 1984, for details). Several constraints on the groundwater levels were introduced during the parameterization process to describe hydro-geologic circumstances. Environmental constraints on groundwater levels were imposed in some subregions as well. Leaching of nitrate to groundwater was described in the model in linear form, too.

Two types of the water extractions were considered: agricultural extractions and public water supply. Demands of public water supply in winter and in summer were given. Agricultural extractions depended on agricultural production, which was described in the model. The agricultural production (as in Section 1.1) was described by means of technologies. A technology is actually a combination of agricultural activities involved in growing and processing of a certain crop or livestock. Technologies differ from each other by their inputs and outputs. Two types of agricultural technologies were considered: technologies that use land and technologies that do not use it. It turned to be convenient to further divide the technologies into the technologies involving livestock and technologies not involving livestock. The following types of inputs (resources) characterize a technology: labor, capital, and water. Land-using technologies are additionally characterized by the input of nitrogen supplied by fertilization. Each technology is also characterized by the output (crop yields, livestock products).

Technologies that involve livestock are additionally characterized by outputs of animal slurries produced as by-products.

Application of agricultural technologies was described in terms of their intensities. For land-using technologies, the intensities had the meaning of areas of land allocated to these technologies. For technologies that do not use land and that involve livestock, intensities had the meaning of a number of livestock-heads. For other technologies, the intensity had the meaning of, say, amount of slurry transported to outside the region.

Inputs of such resources as labor and capital was given by corresponding quantities per unit of intensity of a technology, for example, by amount of labor per unit area of land for a technology. It was also assumed that the water inputs for technologies, which do not use land, are quantified in the same way (amount per unit intensity). However, in the case of water inputs and yields of land-use technologies, the description is different. One reason for this difference is that both the water availability and the output of land-use technologies depend on weather conditions. Another reason is that the availability of water is also influenced by activities in the region, especially pumping of groundwater. In order to take into account the respective possible variations in the performance of land-use technologies, a finite number of options for each such technology are considered that cover a suitable variety of typical water availability situations in each subregion. The term “sub-technologies” was used to describe such options.

Each of sub-technologies in the model was characterized by the crop productivity, by the corresponding seasonal averages of the soil moisture and of actual evaporation, as well as by the total nitrogen requirement per unit area of land. Actually, the “demand” for soil moisture was considered in the model. Satisfaction of the demand together with the satisfaction of the requirement for nitrogen guaranteed obtaining of certain crop productivity. Each of ten land-using technologies were divided into three sub-technologies. Five technologies, which do not use land, were considered, too. The crop production technologies included glasshouse horticulture, intensive field horticulture, extensive field horticulture, production of potatoes, cereals, maize with low nitrogen application, maize with medium nitrogen application and maize with high nitrogen application. The animal production technologies included grassland with high cow density, grassland with low cow density, beef calves breeding, pigs for feeding, pigs for breeding, egg-laying chickens and broilers production.

Soil moisture that played an important role in the model of crop production was related to precipitation and to sprinkling. The sprinkling volume was restricted by sprinkling capacities. Sprinkling from surface water was connected with irrigation. The surface water supply capacity was limited. The moisture content of the root zone in summer was related to the moisture content at the beginning of summer and to the level of groundwater at the end of winter.

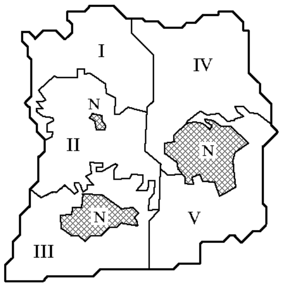


Figure 2.2.1. Five economic clusters of the region. Natural zones are depicted by ***N***

As it was said earlier, the technologies that involve livestock produce animal slurries as by-products that can be used as fertilizers for land-using technologies. Five kinds of slurries were described in the model: cattle slurry, beef calf slurry, pig slurry, chicken slurry and broiler manure. Two directions of slurry application were considered: on the arable land and on the grassland.

Labor requirements were satisfied by the labor of the region and the labor hired from outside of the region.

In our research, the original OW model was aggregated. Two aggregations were used. In the first one, a “model subregion” of the region was obtained. It was used as a “characteristic representative” of the whole region in the framework of analysis of regional agricultural and environmental potential. In the second aggregation mode, the region was divided into five economic clusters, each of them consisting of a number of subregions (see Figure 2.2.1). Though the explored model was aggregated, it was still sufficiently large: it had 460 variables and 672 constraints.

Description of the research

Two environmental and two economic criteria were studied in the research. The two environmental criteria included

- maximal fall of groundwater level in natural zones, h, measured in centimeters; and
- nitrates concentration in deep aquifers, C, measured in milligram per liter of water.

The two economic criteria were:

- investment into agricultural production, I; and
- increment in yearly pure income, W.

Values of both economic criteria were measured in million of Dutch florins. It is clear that one is interested in minimizing both environmental criteria. As to economic criteria, increment in income is preferable. Investment into agricultural production, however, has not any certain improvement direction.

In this study, we applied visualization of the frontiers of the Partial Edgeworth-Pareto Hull (PEPH) to simplify the pictures. It means that we specified improvement direction for only one criterion (additional income W), but not for all of them. However, it turned to be sufficient to make the PEPH convex for this model (in contrast, the variety of feasible criterion vectors is not convex for this model). Due to this, it was possible to approximate it using polyhedral sets and to display by its two criterion slices.

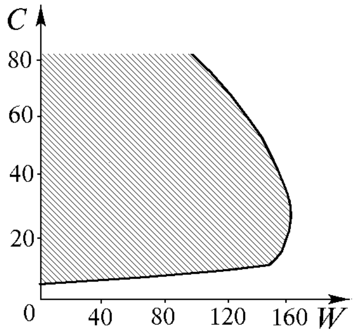
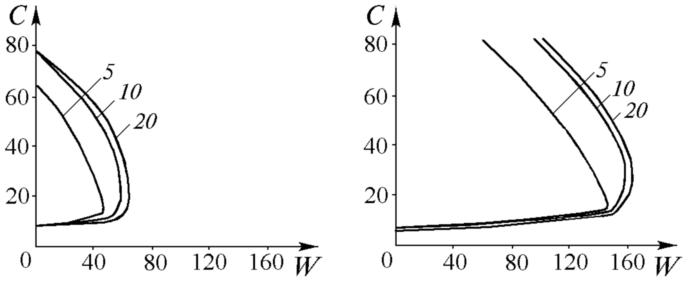


Figure 2.2.2. The frontier for two criteria: income W and nitrates concentration C. Values of C are multiplied by 10.

One of the slices of the PEPH is given in Figure 2.2.2. Increment in the yearly pure income W is located in the horizontal axes, and the concentration of nitrates in deep aquifers C is located in the vertical axes. Pollution values are multiplied by ten. The values of the other two criteria satisfy the constraints $I < I_{\max} = 250$ million florin, $h < h_{\max} = 20$ cm.

The "south-east" frontier of the PEPH in the Figure is of interest. The value $W = 0$ is related to nitrates concentration of $C = 0.8$ mg per liter. The increment in the income W requires first a moderate growth of pollution level, but after a threshold that is clearly visible in Figure 2.2.2 concentration of nitrates starts to grow very fast. The threshold is related to the income of about 150 million. Maximal income of 164 million is related to the concentration of 2.5 mg per liter. So, the relatively small (about 10%) increment in income to its maximal value requires to double the pollution level. Once again, it proves how it is dangerous to maximize economic criteria without proper considering the tradeoff between them and the environmental criteria! Next part of the frontier is not interesting too much – it proves only that the ability to pollute the nature is limited, too.



a) investment is zero b) investment is maximal

Figure 2.2.3. Frontiers for income versus pollution for three values of the fall of the groundwater level

Now let us consider the influence of two other criteria, i.e. of maximal fall of groundwater level in natural zones and investment. This information is given in Figures 2.2.3 – 2.2.4. In Figure 2.2.3a and 2.2.3b, three frontiers among income *W* and concentration of nitrates *C* are given for three values of the groundwater level given. Investment is zero in Figure 2.2.3a, and it is maximal in Figure 2.2.3b. The largest of these slices was displayed already in Figure 2.2.2.

One can see that increment in investment makes the frontiers move, but it practically does not change their shape. However, increment of *h* makes the shape change. The change is visible in the Figure 2.4.3a. It is clear that the increment of *h* from 5 cm to 10 cm results in a substantial growth of income, but its increment from 10 cm to 20 cm gives practically nothing.

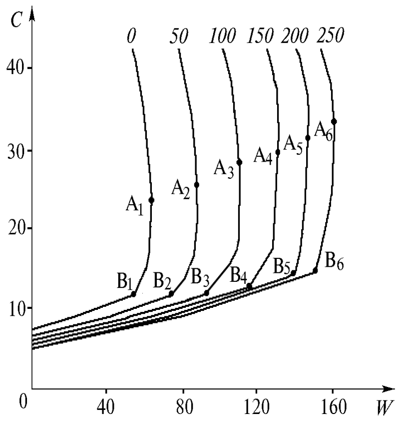
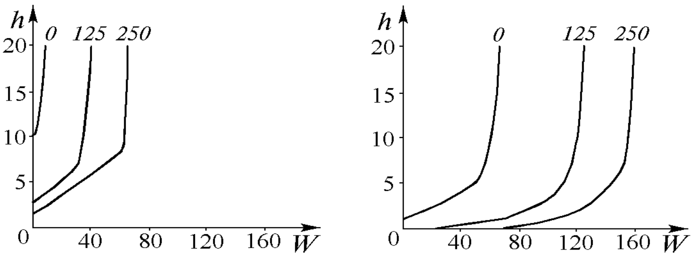


Figure 2.2.4. Frontiers for income and pollution for several values of investment. The fall of the groundwater level equals to 10 cm

Now let us consider the influence of the investment in details. Figure 2.2.4 provides most interesting parts of the slices depicted for the same criteria as in Figure 2.2.3, but for several values of investment specified in Figure 2.2.4. The fall of the groundwater level equals to 10 cm. Once again, it is visible that increment in investment makes the frontiers move, but does not change their shape. One can see how the kink points denoted by ***B1, B2,…, B6*** depend on investment and compare kink points with points of the maximal income ***A1, A2,…, A6***. First of all, it is clear that the locations of points ***A1, A2,…, A6*** are not stable, a minor change in the data can make points to move parallel to the vertical axis.

Here we have met an example that shows that location of points related to maximal criterion values may be not stable. It seems that such situation is a normal feature of real-life problems. It means in turn that the end-points of the non-dominated frontier, which coincide with maximal criterion points, are not stable, too. For this reason, one has not to restrict to the non-dominated frontier (like in the standard decision maps), but to display the whole slice of the

EPH or PEPH (like it is done in the modified decision maps used in the FGM/IDM technique). Figure 2.2.4 is sufficient to prove that it is not reasonable to increase the income beyond the kink level. So, the above instability of points ***A1, A2,…, A6*** is not important: struggling for the maximal income and disregarding environmental aspects is simply stupid in this case. Figure 2.2.3 proves that the same inference is true for all values of the fall in the groundwater level. Note that we do not insist on application of the points ***B1, B2,…, B6***; user has to decide about the feasible goal. It may happen that further water quality improvement is needed.



a) C= 0.8 mg per liter b) C= 2.5 mg per liter

Figure 2.2.5. Frontiers for income versus fall of the groundwater level for several investments

Figure 2.2.5 displays slices of the PEPH for different criteria – frontiers for income versus groundwater level are given depending on investment volumes specified in Figure. In Figure 2.2.5a, nitrates concentration equals to 0.8 mg per liter, and it is 2.5 mg per liter in Figure 2.2.5b. One can see that the frontiers do not touch the horizontal axis in Figure 2.2.5a. It means that it is impossible to provide the initial level of groundwater for this value of nitrates concentration. In contrast, Figure 2.2.5b shows that for higher nitrates concentration a sufficiently large investment can help to avoid the fall in the groundwater level. Non-zero investment means in turn that a change of intensities of agricultural technologies is not sufficient for supporting the groundwater at original level. So, and a non-zero investment into new technologies is needed.

It would be interesting to consider different collections of slices and to discuss the regional strategies related, say, to points ***B1, B2,…, B6.*** However, we cannot do it because of the complexity of the description of a strategy in the model (remind that it is described by 460 variables). Several strategies and other details of the research are discussed in (Kamenev et al., 1986).

Note that a moderate value of investment can solve environmental problems of this region – it can be sufficient for conservation of the groundwater level in natural zones. In this aspect, this region differs drastically from the example region discussed in Chapter 1 where environmental and economic criteria were in a conflict that could not be settled with a minor investment.

2.3. Analysis of strategies for long-term development of a national economy

In this Section, the FGM/IDM technique is applied in the framework of an analysis of the long-term development strategies for a national economy. A simple model, which describes transition process from an “old” polluting technology to a “modern” clean one, is studied taking into account levels of consumption, pollution and unemployment. The Section is based on the paper (Lotov et al., 1992).

Models of economic growth are usually studied in order to gain a better understanding of the general problems of long-term development of a national economy. The problem of distribution of the national income between consumption and investment is usually of special interest (see, for example, Phelps, 1961, and Stoleru, 1967). These studies are based on application of optimization. Here, we demonstrate that multi-objective approach can bring new important results, especially if environmental and social aspects are taken into account.

Description of the model

The potential opportunities for development of a national economy are studied here on the basis of a simple, illustrative model. We consider only one product produced by several technologies that have different economic and environmental features. The product is used both for investment and consumption. Output of a technology is restricted by the capacity of funds that implement the technology. Note that the funds can be used only partially. There exists another constraint that is common for all technologies – the constraint related to the given labor force. If the labor force is used only partially, it is considered as unemployment. Pollution is supposed to be a result of production activities. Pollution destruction is supposed to be proportional to the pollution level. The initial capacities of technologies and the initial pollution are supposed to be given. A sufficiently long time-period is considered (about 50 years).

Three criteria for strategies screening are studied in this Section:

- consumption criterion C^*,
- unemployment criterion U^*,
- pollution criterion Z^*.

For the pollution and unemployment criteria their maximal values during the time-period under consideration are used. The consumption criterion is based on the deviation of computed consumption from a given reference trajectory. For the reference trajectory we apply the trajectory of exponential growth. Consumption and pollution are measured in their initial values, and unemployment is measured in parts of the labor force. The values of the coefficients of the model were selected to be typical for a national economy.

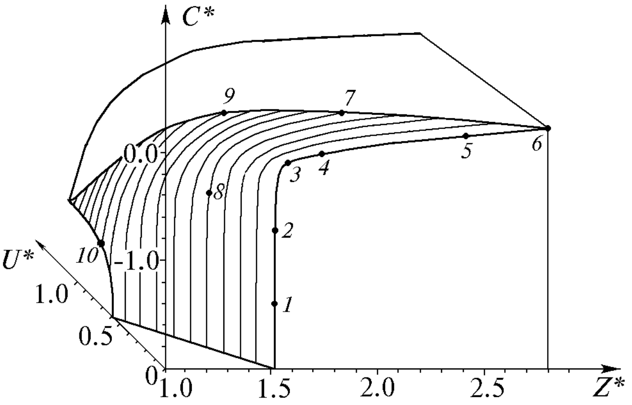


Figure 2.3.1. The EPH for three criteria. The non-dominated frontier is hatched.

Exploration of the non-dominated frontier

Here a model with two production technologies is analyzed. The first one represents the "old" technology that is cheaper than the second, "modern" one. The modern technology is less polluting than the old one. Moreover, the new funds require less labor force, but are more expensive. The requirements for labor force decrease in time for both technologies. It is clear that the increment in the consumption criterion and the decrement in the pollution and unemployment criteria are needed.

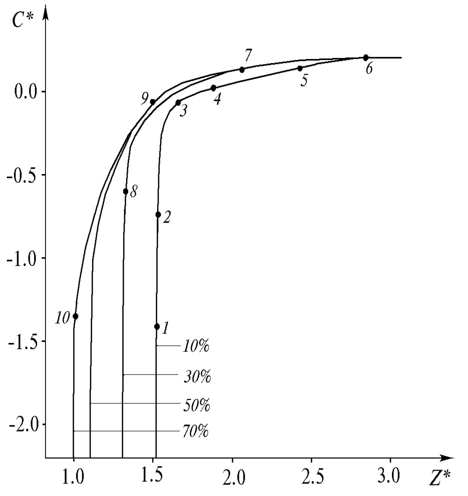


Figure 2.3.2. The decision map

Figure 2.3.1 displays the three-criterion EPH for the model under study. The non-dominated frontier is hatched. This picture provides a good understanding of the general structure of the EPH and its non-dominated frontier, but at the same time it seems to be impossible to understand the criterion tradeoffs (substitution rates) or even recognize coordinates of non-dominated points in this picture. For example, it is pretty complicated to evaluate the criterion values related to the points identified in the picture. However, the decision maps can help.

A decision map is given in Figure 2.3.2. The non-dominated frontiers are given for pollution and consumption while the value of maximal unemployment is restricted for any frontier. The constraints imposed on maximal unemployment are given in Figure 2.3.2; they vary between 10% and 70%. One can see that the decision map provides tradeoff information in a more clear form than the three-criterion picture given in Figure 2.3.1 – one can easily understand how pollution is transformed into consumption if the efficient subset of strategies is used. The points, which were identified in Figure 2.3.1, are marked in the decision map, too. In contrast to the three-criterion picture, user can easily understand the criterion values of these points in the decision map.

All the four frontiers of the decision map given in Figure 2.3.2 have the same shape. Three well-defined zones can be seen:

1) the first zone, in which a small increment in pollution results in substantial growth of the consumption;

2) the second zone, where the consumption growth is related to a substantial increment in pollution;

3) the intermediate (or elbow) zone.

The intermediate zone is fairly small for the frontier related to the maximal unemployment of 10%, but it gets broader when maximal unemployment increases to 70%.

In the second zone, values of consumption are pretty close to the reference trajectory (*C** is close to zero). The non-dominated frontiers between pollution and consumption are close one to another. This means that the constraint imposed on the unemployment has a small influence on the frontier in this zone. In contrast, increment in unemployment can help to decrease the pollution value in the first zone (consumption is low, and * is less than –0.5). For example, if * = –1, the increment in maximal unemployment from 10 to 30% helps to decrease pollution from 1.5 to 1.3. Surely, this is a very high price to pay for a relatively small decrement in the pollution value. Pollution decrement is even less in other points. Therefore, the frontier with minimal unemployment (10%) seems to be of interest. Since the intermediate zone is fairly small for this frontier, it has a "kinked" form. Point ***3*** is located near the kink. It is related to a small deviation from the reference trajectory (* = –0.1), while pollution is about 1.7. To make pollution a bit less, one needs to decrease consumption drastically (to * = –0.7 in point ***2***). An increment in consumption at this point requires substantial increment in pollution (to * = 0.05 and Z^* = 2.5 in point ***5***). For these reasons, point ***3*** seems to be fairly reasonable.

Exploration of strategies

Strategies associated to points in Figures 2.3.1-2.3.2 were computed. We consider the strategy that results in point ***3***. The strategy is given in Figure 2.3.3, where five graphs are depicted that describe the time dependence of the variables. Ten time periods are considered, each of them corresponds to five years. The following variables are depicted in Figure 2.3.3: pollution Z, unemployment U, capacities of first and second technologies $_1$ and $_2$, output $_1$ of the second technology (output of the first technology coincided with its capacity).

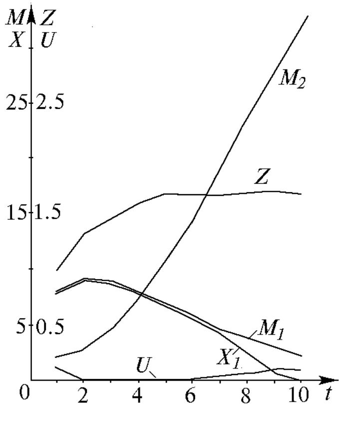


Figure 2.3.3. Strategy with a balanced consumption/pollution

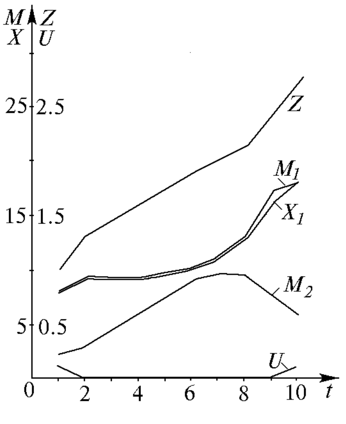


Figure 2.3.4. Strategy with maximal consumption

One can see that at the very end of the time interval, the second (new) technology substitutes the first (old) one. However, the substitution is fulfilled not at once, by gradually. During the first part of the interval (about 10 years), the capacities of the first technology are growing. Only after it, they start to decline. Full utilization of the capacities of the first technology stops only at the very end of the interval. So, the transformation of the economy takes about 50 years. The unemployment is small in the middle of the time interval. Its reappearance at the end of the time interval seems to be related to high efficiency of the second technology. Pollution gradually approaches the level of 1.7 that seems to be natural for the second technology.

Now let us compare the above strategy with the strategy that is associated with point ***6***, which is characterized by the maximal consumption. The same five graphs are depicted in Figure 2.3.4. The main feature of Figure 2.3.4 is evident – the substitution of the first technology by the second technology does not happen! The capacities of the second technology start to rise first, but then they decline – the product is used for consumption, and so it is impossible to construct capacities based on the new technology that is more expensive than the old one. A permanent substantial growth of the pollution is clearly related to the extensive application of the first technology.

Strategies related to other points from Figure 2.3.2 are given in the paper by Lotov et al. (1992), where several additional features of the study are discussed, too.

It is extremely interesting to compare the development strategies that are associated with points ***6*** and ***3***. Though point ***6*** is related to the maximal consumption, the difference between point ***6*** and point ***3*** is not so large in this aspect – in point ***6*** it holds $C^* = 0.1$ instead of $C^* = -0.1$ in point ***3***. However, this small difference results in extremely negative effects – the strategy associated with point ***6*** brings the nation into a catastrophic environmental situation and economic deadlock. In contrast, the strategy associated with point ***3*** results in the complete modernization of the economy and in a stable relatively small pollution level.

This example is very educative. It proves that a single-criterion optimization (say, optimization of consumption) cannot be sufficient in the process of searching for reasonable development strategies – the single-criterion optimization results in inappropriate values of other performance indicators. We'll meet the same effect in other problems studied in this book.

2.4. Screening Support for Trans-boundary Air Pollution Control

In this Section the FGM/IDM technique is applied in the framework of software that supports searching for strategies aimed at the abatement of long-distance air pollution. User of the software can apply screening of possible strategies using an integrated model that consists of two parts: a regional sulfur abatement cost model and a model of sulfur transportation between regions of several countries. Screening criteria may include sulfur deposition rates and abatement costs in some or all of the regions. This Section is based on the paper (Bushenkov et al., 1994).

Introduction

Acid rain is one of the major environmental concerns in Europe. It is known to render lakes incapable of supporting aquatic life, to threaten forest and agricultural productivity and to damage statuary and other exposed materials. Airborne concentrations of sulfate particles can also increase morbidity and even premature mortality. Sulfur 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. Cooperation among the countries concerned is a natural solution to the problem. In fact, natural approach to studying the economics of acid rain consists in its formulation as an international decision problem.

A key problem 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 benefit from abatement reduction? As Maeler (1990) and Kaitala et al. (1992) have demonstrated, cooperation may entail side payments, which are a stark reality in international cooperation.

The main goal of the FGM-based software described here is to provide new opportunities for studying international acid rain problems and for elaborating reasonable abatement strategies that may be related to software described here. As usually in the FGM/IDM technique, collections of two-criterion non-dominated frontiers of the variety of feasible criterion vectors are displayed. The FGM/IDM technique is used to study acid rain in Finland, Russia and Estonia. In 1989 the governments of Finland and the former USSR 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 political events of 1991 have made this agreement obsolete. Finland has responded to the change in the international environment by seeking for cooperation with the new nations. In particular, the government of Finland has decided to develop a program of environmental investment in areas that are the sources of transboundary air pollutants deposited in Finland. Supporting the decision making is required in the framework of the program.

The FGM/IDM technique can help to solve this kind of problems. Users, e.g. experts of the governments of the countries involved, can study the feasibility frontiers of sulfur deposition rates and abatement costs in the individual countries as well as the tradeoffs among these criteria. This information is obtained from a sulfur transportation model and from estimated abatement cost functions. The FGM/IDM technique supports a search for appropriate feasible combinations of criterion values and associated abatement strategies.

Data and the model

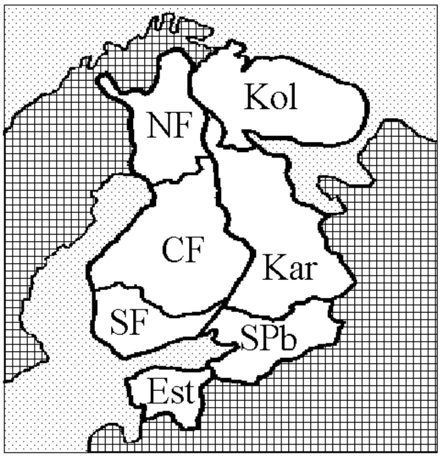


Figure 2.4.1. Map of the region

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

Depositions were calculated in (Tuovinen et al., 1990) by applying the latest version of the long-range transport model for sulfur developed at the Western Meteorological Center of the European Monitoring and Evaluation Program (EMEP). Emission data approved by the Finnish-Soviet Commission were used as inputs of our model. Finland is divided into three sub-regions

(Figure 2.4.1): Northern (NF), Central (CF) and Southern Finland (SF). The areas close to the eastern border of Finland are divided into four areas: Estonia (Est) and three areas in Russia: Kola peninsula (Kol), Karelia (Kar) and St. Petersburg (SPb). The annual sulfur depositions per square meter range from 0.5-0.6 gram in Northern and Central Finland as well as in Karelia to 1.2-1.3 gram in Southern Finland and Estonia.

In (Tuovinen et al., 1990), an annual sulfur budget between these seven regions was estimated for the year 1987. It can be used to formulate a sulfur transportation matrix indicating how the emission in one area is transported in the atmosphere for deposition in another. The columns of Table 2.4.1 specify the distribution of deposition of one unit of sulfur emitted in each area between the regions. The large numbers on the diagonal show own sources of pollution play an important role in each region. The sums in a column (or a row) may be not equal to one since the regions both emit sulfur to and receive it from the rest of the world.

Table 2.4.1. Deposition distribution

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

A sulfur transportation model was constructed on the basis of emission data and data provided in the table. Let E and Q denote the vectors of annual emission and deposition of sulfur, respectively, and let A stand for the matrix given in the table and B for the vector of exogenous deposition in 1987. The model can then be expressed in vector notation as

$$Q = AE + B.$$

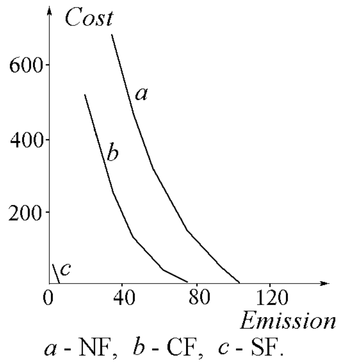


Figure 2.4.2. Cost functions for Finland

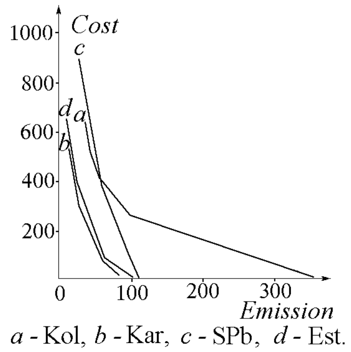


Figure 2.4.3. Cost functions for Russia and Estonia

To apply this model to the analysis of cooperation on trans-boundary air pollution between the three countries we need information about both future emissions and sulfur abatement costs. Finnish Integrated Acidification Assessment model (HAKOMA) provided the estimates for the emissions in the year 2000 (Johansson et al. 1991). The Finnish estimates of future emissions were obtained by using the basic energy use scenario of the

Ministry of Trade and Industry. The Russian and Estonian emissions were assumed to stay at their 1987 levels, as no other information was available.

The estimates for sulfur depositions were obtained from the above model by using the estimated emissions and by assuming thatthe man -made sulfur deposition originating from the rest of the world will be 50 per cent lower that in 1980. We justify this assumption by referring to the Helsinki protocol of the Convention on Long-Range Trans-boundary Air Pollution according to which the 21 signatories will reduce their sulfur emissions by 30 per cent from the 1980 levels. Moreover, about half of these countries have declared more ambitious cuts ranging from 40 to 80 per cent.

The sulfur abatement cost function for the regions were calculated for various sulfur reduction requirements ranging up to the maximal technologically feasible removal. The HAKOMA project at the Technical Research Center of Finland (VTT) has derived such cost functions for Finland and the nearby regions (Johansson et al. 1991). These piecewise linear functions (Figure 2.4.2) are used in the software but other cost estimates can also be applied easily. The annual costs, measured in million Finnish marks, have been estimated on the basis of expected emissions for the year 2000, and they include both capital and operating costs.

The sulfur transportation model and the cost functions developed above provide an opportunity to formulate performance indicators that can be used as possible screening criteria. User can use the following six groups of performance indicators:

- sulfur abatement cost in each sub-region;
- abatement cost in Finland, in the nearby region of Russia, and in Estonia;

- total abatement cost for the whole territory;
- average sulfur deposition in each sub-region;
- maximal average depositions in the sub-regions of Finland, Russia, and Estonia;
- maximal average depositions in the whole territory.

Search for a trans-boundary acid rain abatement strategy

The search for preferable strategies based on application of the FGM includes the following main stages:

1) problem formulation (defining the criteria and constraints);
2) compatibility test;
3) construction of the variety of feasible criterion vectors;
4) visual exploration of the non-dominated frontier of the variety by slices;
5) identification of a feasible goal;
6) computing the goal-associated efficient strategy;
7) decision display.

User has first to specify criteria in the list of performance indicators (i.e. costs and deposition values), that includes

1) regional cost related to the emission decrement;
2) national (for Finland or Russia) cost related to the emission decrement;
3) total abatement cost;
4) maximal rate (in gram per square meter) of sulfur deposition in any sub-region;

5) maximal rate of sulfur deposition in country (Finland or Russia);

6) maximal rate of sulfur deposition in the whole territory.

The direction of criterion improvement should be indicated by user, too. Initially, it has been supposed that user is interested in minimizing the criterion values, but it is also possible to assume the opposite type of interests (say, maximization of investment in a particular region). It may sometimes be the case that user does not know about the improvement direction of a particular criterion. This situation can be specified as well. For this reason, we do not construct the EPH of the variety of feasible criterion vectors, but the variety itself.

Then user has an option to define constraints imposed on the values of performance indicators. Say, maximal rate of sulfur deposition can be specified in any sub-region, country or the whole territory. The initial values of pollution deposition are restricted from above by the values corresponding to the forecast for the year 2000. Since these values are treated in the model as the pollution depositions associated with zero cost, these constraints cannot be violated by any feasible decision. They are displayed to inform user.

After criteria and constraints have been specified, the compatibility of the constraints is checked. If the constraints are not compatible, user has to return to their definition. If they are compatible, the variety of feasible criterion vectors or a related set is constructed. As usually, visual exploration of the variety is based on displaying its two-dimensional slices. Then, a preferred feasible point should be identified on one of the slices. Afterwards, the associated with it efficient strategy is computed automatically. Any strategy obtained in this way can be studied in more detail by displaying it as a table, diagram or histogram.

Let us consider an example. Suppose user has specified three criteria:

1. abatement cost in Finland (CF, in million Finnish mark, FIM);
2. total abatement cost (TC, in billion FIM);
3. maximum deposition rate in Finland (PF, in gram per square meter).

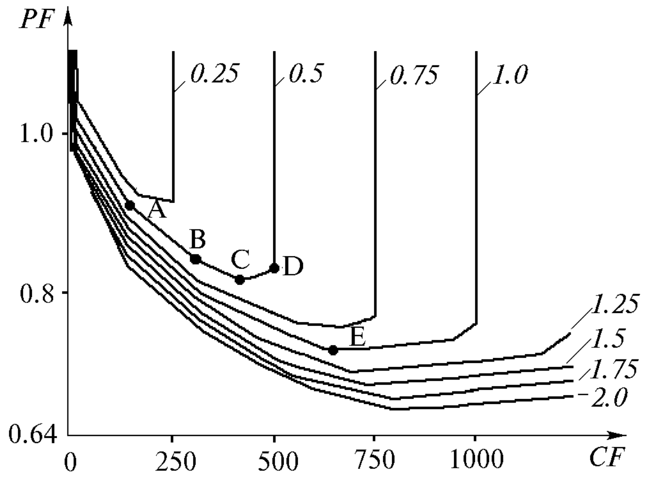


Figure 2.4.4. Frontiers of the variety of feasible criterion vectors

It is assumed that the decrement in the second and the third criteria values are preferable. The direction of improvement of the first criterion is not specified. Let us suppose the following constraints were imposed:

1. the deposition rate in the Northern Finland must be not be greater than 0.4 gram per square meter
2. the deposition rate in the Central Finland must not be greater than 0.5 gram per square meter.

The constraints are compatible, and the variety of feasible criterion vectors can be constructed and visualized (see Figure 2.4.4).

In the Figure 2.4.4 several frontiers of the variety of feasible criterion vectors are depicted in the plane of the criterion CF (investment in Finland) and the criterion PF (maximum deposition rate in Finland) for several values of total abatement cost. The range of total costs in the whole region is between zero and 4.1 billion FIM. The following total cost values were selected:

TC = 0.25, 0.5, 0.75, 1.00, 1.25, 1.50, 1.75, and 2.00 billion FIM.

Let us consider the properties of the frontier TC = 0.5 that is related to the total cost of 500 million FIM. First of all, it is clear that the increment in the investment in Finland from zero to about 400 million FIM (points ***A***, ***B*** and finally ***C***) results in a gradual decrement in the deposition rate in Finland. Say, 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 about 0.9 gram per square meter. Increasing the Finnish share of the total costs (points ***B*** and ***C***) yields even better result for Finland since the deposition rate decreases. However, increasing this share from 400 million FIM (point ***C***) to 500 million (point ***D***) does not yield a better result: the deposition rate in Finland increases. So, investment in point ***C*** is related to minimal the deposition rate in Finland (a little bit more than 0.8 gram per square meter). Note that the total cost remains the same. This means that, given the total amount of 500 million, all investments exceeding about 400 million FIM give better results when invested somewhere else.

So, investment of 400 million FIM in Finland from the total cost of 500 million FIM corresponds to Finnish interests. It is clear that 400 million FIM must be invested by Finland. Though the software informs where the investment of 100 million FIM must be applied (it is sufficient to consider the associated strategy), what country will pay the balance of 100 million FIM? The software is not supposed to answer this question – the answer must be a result of further negotiation. However, it is clear that the above allocation of total cost is related to the interests of Finland, and other countries may propose different allocations (that may be found using the same software). So, negotiation results may depend upon the source of investment.

Comparison of the curve for 500 million FIM with the other curves given in Figure 2.4.4 informs user concerning the influence of total costs. If total cost equals to 400 million FIM, Finland is interested in application of the whole investment at Finnish territory. This means that in the case of small investment, Finland may be not interested in providing the international aid. In case the total investment is 1 billion FIM, it would be reasonable for Finland to select point ***E*** on the related curve: increasing the investment in Finland beyond this point (if the total costs remains the same) starts to increase the deposition rate in Finland! At point ***E***, abatement cost in Finland is 650 million FIM. Thus, 350 million FIM is reasonable to invest in the neighboring regions.

Let us consider the abatement strategy associated with point ***E*** in additional details. The performance indicators of the strategy are given in Figures 2.4.5-2.4.7. Figure 2.4.5 displays allocation of the total abatement cost among regions, Figure 2.4.6 displays sulfur emissions before and after the investment would be applied, and

Figure 2.4.7 displays the sulfur depositions per square meter before and after the investment.

According to Figure 2.4.5 the optimal strategy consists in investment application mainly in Southern Finland. However, sulfur emissions must be reduced in St. Petersburg and Estonia, too. Estonia pollutes the atmosphere of Southern Finland heavily, so most of the investment in foreign regions (260 million FIM) must be applied there. The rest (90 million FIM) must be applied in St. Petersburg. Perhaps the most surprising result in this case is that the emission in the Kola region must remain unchanged. As to the decrement in sulfur deposition, it is especially substantial in Southern Finland and Estonia, but in St. Petersburg and other regions it is visible, too.

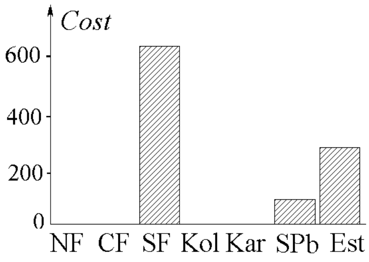


Figure 2.4.5. Cost allocation

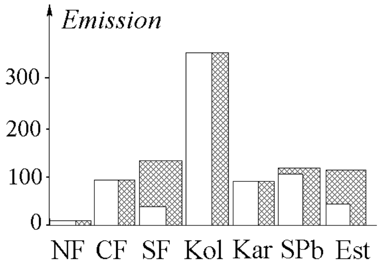


Figure 2.4.6. New versus old emissions

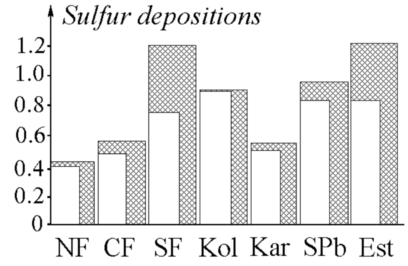


Figure 2.4.7. New versus old depositions

It is important to note, that in the above study, the criteria were selected, frontiers were explored and the goal point was identified in the interests of a Finnish user. Absence of the investment in

Kola is clearly related to the level of admissible pollution in Northern Finland. Exploration of five criteria could make the study more fruitful. Surely a study of Estonian or Russian user would result in different strategies. Let us add that the software turned to be a prototype of several systems.

2.5. Searching for smart strategies for abatement the global climate change

This Section is devoted to the development of a software tool that can help to analyze the global climate change. The tool is based on the FGM/IDM technique, and it must support the process of searching for efficient abatement strategies. Here we outline a demo version of the tool. More detailed description of the research that was carried out in the beginning of 90s is given in (Lotov et al., 1997b and 1999b).

Introduction

Any model system for the development of efficient strategies for abatement of the global climate change must contain at least four submodels:

- a model that describes emission of carbon dioxide and other gases that are responsible for the global climate change; it must describe the influence of economic and technological decisions on the emission;
- a model of global cycle of the above gases; the model must relate the concentration of the greenhouse gases in the atmosphere to their emission;
- a climate model that describes consequences of changing the concentration of the gases; it is important that the consequences in different parts of the world must be estimated;

- a model that describes the influence of climate changes on economic development and standards of life in particular groups of nations.

In the demo version of the model, we decided to restrict to the influence of investment into the energy sector.

The objective of our research is to develop a software tool that could help in the process of searching for smart strategies that result in the decrement in carbon dioxide emission, but in a relatively cheap way. This tool is based on the same ideas as the software for the abatement of trans-boundary acid rains.

Model

In the demo model, which was developed in the beginning of 90s, five groups of nations were considered:

1) post-industrial countries;
2) post-socialist countries;
3) new industrial countries;
4) Asian communist countries;
5) developing countries.

The grouping is depicted in Figure 2.5.1.

The climate change during the time period 1990-2050 was studied (actually, six decades were considered in the integrated model). In the demo tool, the only greenhouse gas was considered, namely carbon dioxide. The carbon dioxide emission was a function of energy consumption, which depended on the gross domestic product (GDP) and energy consumption per unit of the GDP. The energy consumption per unit of the GDP, in turn, was supposed to be able to decrease due to special kind of investment aimed at its decrement (energy-related investment). The GDP for a group of nations was estimated by forecasting the population growth and the dynamics of the GDP per capita.

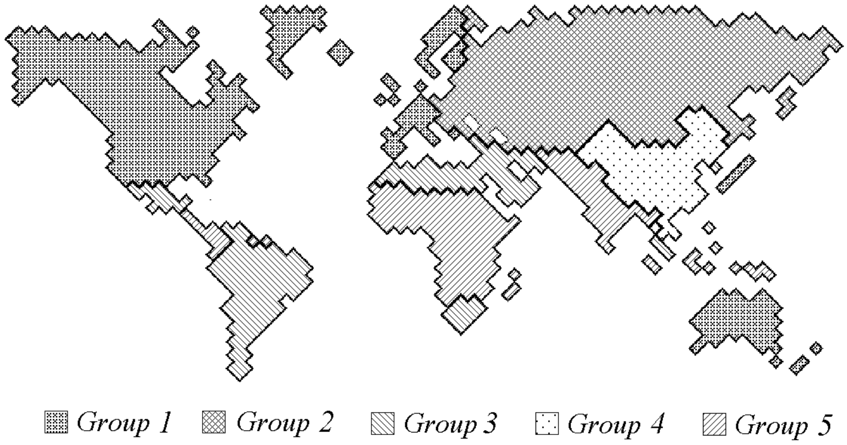


Figure 2.5.1. Five groups of nations considered in the demo model

A simple linear model was used to describe the global carbon dioxide concentration in atmosphere. Its coefficients were identified on the basis of monitoring data. The climate model used was a parameterization of the global circulation model elaborated at the Computing Center of Russian Academy of Sciences in 80s (Moiseev et al., 1983). Simulation experiments with the model helped its authors to develop a linear parameterization of the model, in the framework of which average changes in solar radiation, precipitation and temperature in all world regions were related to the global carbon dioxide concentration.

Professor Alexander M. Tarko estimated the influence of the climate changes (changes of solar radiation, precipitation and temperature in world regions) on economic development and standards of life in particular groups of nations (to be precise, the losses due to climate change). We use this opportunity to express our gratitude to him.

The demo tool was coded for PC. User had to specify several decision screening criteria that are of interest to him/her. Then, the EPH for these criteria was constructed, and users were able to explore its non-dominated frontiers.

Application of the software tool

Let us consider an example, in the framework of which five criteria were explored:

- *I1, I2, I3* = discounted energy-related investments during the whole time period (1990-2050) in the first, second and third group of nations, respectively;
- *I4* = discounted energy-related investment for the whole time period in both the fourth and fifth groups of nations;
- *Ls* = investment related decrement in global discounted losses during the whole time period.

All values are given in billion of US$.

As usually, analysis was based on the exploration of various decision maps in interactive mode. Black and white copy of a decision map is provided in Figure 2.5.2. Here, discounted investment for the whole time period in the first group (post-industrial countries) is given in horizontal axis. Discounted investment for the whole time period in the second group (post-socialist countries) is given in vertical axis. The shading in Figure 2.5.2 (colors in display) is related to decrement in *Ls*. Non-dominated frontiers were related to five values of *Ls* (300, 240, 180, 120 and 60). The values of *I3* and *I4* are not higher than 30.8 and 10 billion, respectively.

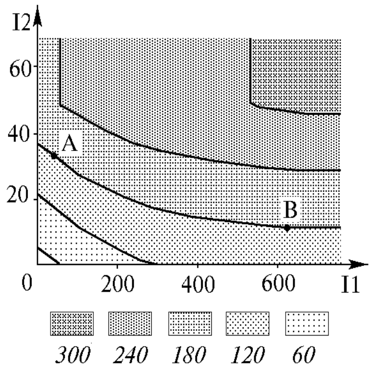


Figure 2.5.2. A black and white copy of a decision map

The non-dominated frontiers in Figure 2.5.2 provide extremely important information. Let us consider points ***A*** and ***B*** on the frontier related to *Ls* = 80 billion. By moving the goal from point ***B*** to point ***A***, user can substantively decrease the required energy-related investment in the first group (38 billion in point ***A*** instead of shocking value of 630 billion in point ***B***) by a relatively minor increment in investment in the second group (34 billion in point ***A*** instead of 12 billion in point ***B***). So, additional investment of 22 billion in the second group can save about 600 billion of investment in the first group!

This impressive knowledge has simple interpretation: energy consumption per dollar of the gross domestic product is about three (!) times higher in the second group than in the first one. Therefore, a decrement in energy consumption (and the related decrement in carbon dioxide emission) is much more expensive in the post-industrial nations than it is in the post-socialist nations. This example shows how the non-dominated frontiers may help experts and politicians to find efficient strategies for abatement of the global climate change.

To study the influence of *I3* and *I4* on the relations among *I1, I2* and global losses, one can use a matrix of decision maps, say, the matrix given in Figure 2.5.3. We remind that a matrix of decision maps can be considered as a collection of snap-shots obtained in the process of animating a decision map. So, the matrix given in Figure 2.5.3 can be related to animation of Figure 2.5.2. However, such interpretation of the decision map matrix is not obligatory.

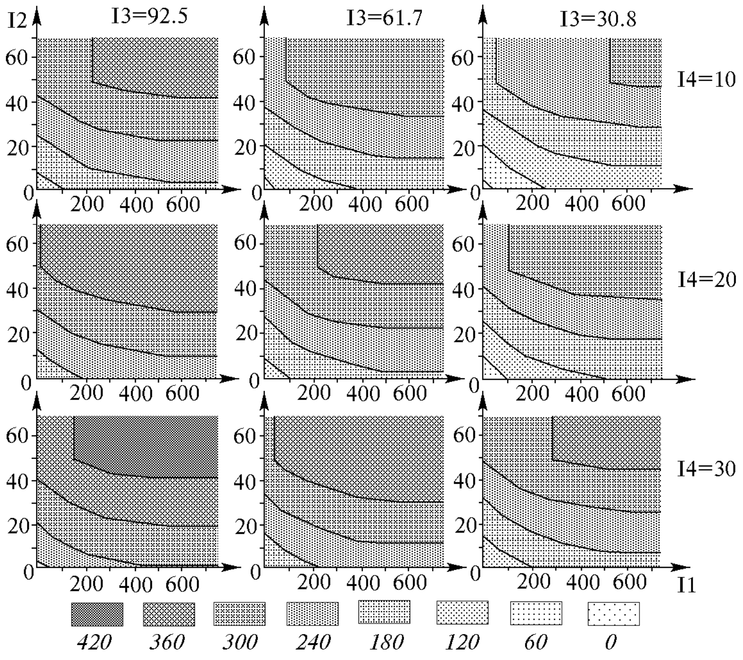


Figure 2.5.3. Black and white copy of a decision map matrix

Any column of the matrix in Figure 2.5.3 is related to a certain constraint imposed on the value of *I3* (constraints are given above the columns), and any row is related to a constraint imposed on the value *I4* (it is given to the right from the row). Only three values of *I3* and *I4* are selected in Figure 2.5.3, and so only nine decision maps are given in the matrix. The decision map given in Figure 2.5.2 is located in the right upper corner of the matrix. Once again, the FGM/IDM-based software provides an opportunity to select larger numbers of decision maps in a column or a row, depending on user's desire and quality of display.

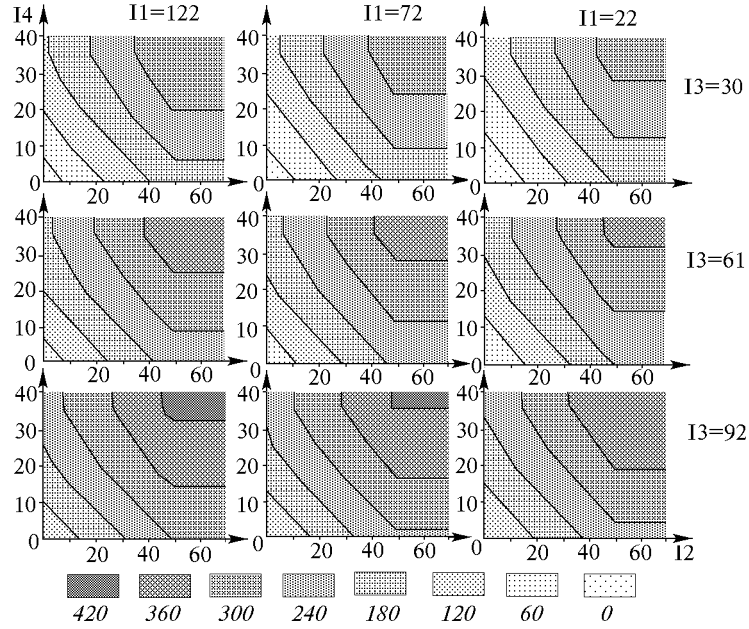


Figure 2.5.4. Black and white copy of a matrix of decision maps for an alternative arrangement of criteria

Shading in Figure 2.5.3 is related to a bit broader range of decrement in global losses than in Figure 2.5.2. The matrix of decision maps shows that the non-dominated frontiers for *I1* and *I2* have the same shape on all decision maps. So, the modification of the values of *I3* and *I4* does not influence our conclusions concerning energy-related investments. Influence of the values of I3 and I4 on the global losses is evident from the picture.

Now let us have a look at non-dominated frontiers for other pairs of criteria. It is interesting that the non-dominated frontiers for *I1* and *I4* look just the same (surely the particular numbers are different). For this reason we do not display related decision maps here. Instead, in Figure 2.5.4 the matrix of decision maps containing the non-dominated frontiers for *I2* (post-socialist countries) and *I4* (Asian communist countries and developing countries) is displayed. The shadings are related to the same values of decrement in losses as in Figure 2.5.3. The values of *I1* are related to columns, and the values of *I3* are related to rows.

One can see that the non-dominated frontiers between *I2* and *I4* have a different shape than the frontiers between *I1* and *I4*. Now it is impossible to save investment in the way displayed in Figure 2.5.2. This result has a simple interpretation: both groups of nations have the analogous pattern of energy consumption.

Let us consider one of the decision maps, where the investment *I1* is not greater than 72 billion, and the investment *I3* is not greater than 92 billion (Figure 2.5.5). Let us consider, for example, points ***A*** and ***B*** on the non-dominated frontier related to *Ls* = 300 billion. In point ***A,*** it holds *I2* = 50 billion and *I4* = 3 billion. In point ***B,*** it holds *I2* = 11 billion and *I4* = 36 billion. So, the sum of the energy-related investments is approximately the same, and, in contrast to the case of *I1* and *I2*, it is impossible to receive a substantial decrement in investment by transferring it from one group of nations to another. According to the matrix of decision maps given in Figure 2.5.4, the above property holds for all decision maps.

As usually in the FGM/IDM-based applications, selecting a preferred strategy is based on identification of a feasible goal. Point

C in Figure 2.5.5, which is related to the maximal value of *Ls* in this decision map, was selected to be the goal. Time dependence of investments and decrements in losses (not discounted now) are displayed in Figure 2.5.6 for the strategy associated with point ***C*** in Figure 2.5.5.

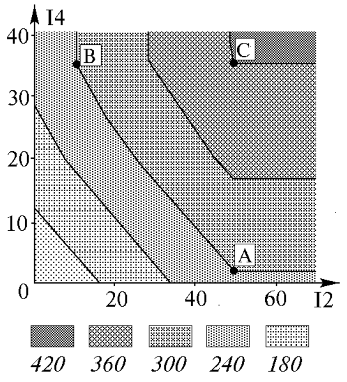


Figure 2.5.5. One of decision maps for *I2* and *I4*; *I1* is not greater than 72 billion, and *I3* is not greater than 92 billion

In accordance to the number of the groups of nations, there are five vertical sections in Figure 2.5.6. In any section, two column diagrams are given. The columns above zero line display decrement in losses for the group (measured in percents of the GDP) depending on time period (once again, six decades are considered). The shaded columns beneath zero line display investment into energy sector (measured in percents of the GDP, too). One can see that maximal investments (in percents of the GDP!) must be sufficiently large everywhere outside the post-industrial countries, where the investment is relatively low. However, taking into account that the GDP is much higher in post-industrial countries, real investments are not so different.

We do not provide additional details because of the methodological nature of our research. It is interesting that main part of investment must be done at the beginning of the time period, while the result, that is decrement in losses, is expected mainly at the end of the period.

It is important to stress that the analytical software tool described in this Section is based on the models, only part of which (actually, climate model) can be considered as the result of a careful research.

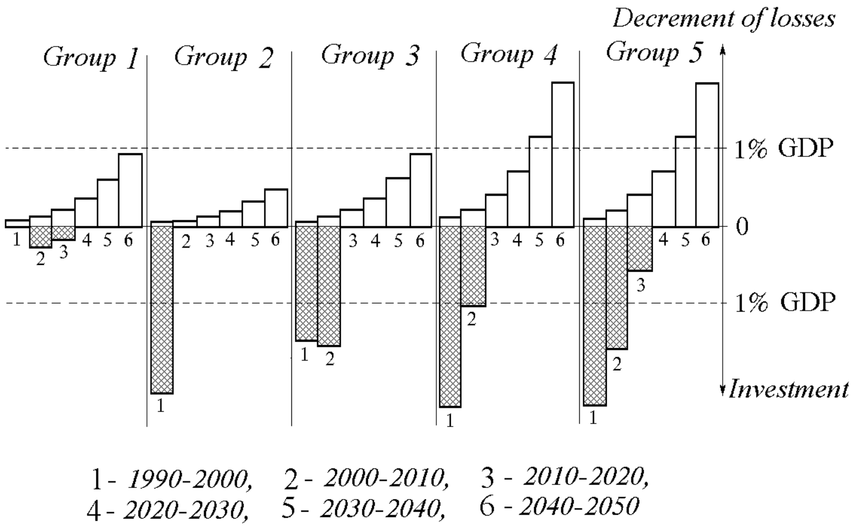


Figure 2.5.6. Time dependence of investments and losses for the groups of countries

Other submodels are fairly schematic. Moreover, many features of the research are out of date. Therefore, to apply the described approach in a real-life development of smart strategies for the global climate change abatement, one has to base the study on more detailed and comprehensive models. However, even the rough models used in this research prove that it is important to search for such global climate change abatement strategies that do not have destructive influence on the economic growth of particular countries and the world economy as a whole.

Conclusion

In this Chapter, several methodological applications of the FGM/IDM technique were described. They show that the technique can be effectively used in a broad range of environmental decision problems. The next Chapter is devoted to several real-life applications of the technique.