

WORKING PAPER

TRANSBOUNDARY AIR POLLUTION IN EUROPE: AN INTERACTIVE MULTICRITERIA TRADEOFF ANALYSIS

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FOREWORD

The acid rain problem has recently captured the interest of researchers from all over the world. For a good number of years, IIASA has played a leadership role in researching the impacts of air pollution, in particular through the development of the RAINS model.

The present research paper addresses the important issue of building a decision support component for analyzing the complicated transboundary problem of balancing the deposition levels of sulphur in Europe and the costs associated with reducing sulphur emissions. The interactive nonlinear multicriteria package DIDAS-N, which was in part developed within the SDS program at IIASA, is used to illustrate the relevant concepts.

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ABSTRACT

In this paper, the acid rain problem in Europe is discussed, stressing the transboundary tradeoffs between abatement costs of sulphur emission reduction and corresponding deposition levels in the different countries. An interactive decision support methodology is proposed which utilizes a powerful nonlinear multicriteria software package to evaluate various scenarios and tradeoffs. The concepts are illustrated using previously published data. The results from the tradeoff analysis show that reasonable deposition levels can be reached with limited transfers of funds between countries. The extent of these transfers can be controlled by selecting appropriate target levels for the criteria across countries.

INTRODUCTION

Nowadays acid rain is one of the major environmental concerns in Europe. Yet, as many other problems, the problem of acid rain is not new. Over 300 years ago, the English nobleman John Evelyn presented an essay titled "Fugifugium or the Inconvenience of the Aer and Smoake of London Dissipated, together with some Remedies Humbly Proposed," to King Charles II (Evelyn 1661). In his essay, Evelyn already proposed the theory that sulphur originating from smoke caused by burning coal turns silver black and destroys iron and stone. In the following centuries the awareness of this problem has grown, and more and more has been done to avoid the negative impacts of pollution, especially at the local and regional level.

Over the last few decades the scale of environmental problems has shifted dramatically from the local and regional level to a continental (acid rain) and global (greenhouse effect) level. The primary reason for this shift is the fact that the problem has now become transboundary, in that emissions in one country affect the environmental quality in other countries, and at the same time the environmental quality in a given country is affected by emissions from other countries.

In this paper the focus is on acid rain in Europe, and more specifically on the transboundary problem of tradeoffs between and balancing of costs and benefits of abatement policies across countries in Europe. The costs of emission reduction consist of the expenses associated with abating air pollution originating from sulphur dioxide (SO_2) and nitrogen oxides (NO_x). Power plants, oil refineries and other industries, as well as transportation and the domestic sector are to a large extent responsible for these emissions. The benefits of abatement measures include decreased damage to materials, buildings and ecosystems, particularly forests and aquatic systems.

For several reasons it is difficult to balance costs and benefits of emission reduction. The first reason is that costs and benefits may not accrue to the same country, so that the acid rain problem calls for international environmental policies and negotiations in order to determine how much each country should abate and how much each country should pay for abatements in other countries. The second reason complicating the analysis is that benefits cannot easily be expressed in terms of monetary figures, so that preferably a comparison of costs and benefits would involve direct tradeoffs in relevant physical units.

The purpose of our paper is to gain insight into the decision dynamics of this complicated problem, by exploring the nature of tradeoffs between abatement, the associated costs incurred by each country, and deposition levels throughout Europe. In order to analyze this issue, we utilize a simplified version of RAINS (Regional Acidification Information and Simulation) (Alcamo et al. 1987), an integrated model which has been developed to link emissions and depositions in Europe, to provide the necessary data. The RAINS model can

be used to simulate the effects of various different energy scenarios and abatement technologies. For our purpose, the information provided by RAINS relates on the one hand to estimates of the cost functions associated with abatement by each of the 27 European countries considered, and on the other hand to the effects in terms of deposition levels for various different abatement policies by these countries. A list of the 27 countries can be found in the first column of Table 1 below.

The information provided by RAINS is used as input into an interactive multicriteria decision support system which serves to analyze the tradeoffs between various different policy scenarios, in terms of the cost and deposition levels for each country. In this system, the effects of various different target levels for the deposition and abatement costs for each country can be explored in one single interactive computer session. In this session, the decision maker modifies the target levels at each stage as he deems appropriate, after which the computer model calculates a new recommended solution based upon these modified values.

Our approach differs from previous studies in that 1) benefits do not have to be expressed in terms of monetary units or utile values, 2) the abatement costs and depositions of each country can be considered separately, or alternatively groups of countries can be considered, 3) the analysis is interactive, so that various different scenarios and tradeoffs can be evaluated in a short period of time, and 4) the effects of limited transfers of funds between countries on emissions and depositions can easily be calculated. Such limited transfers are more reasonable in practice than transfers of large amounts of money. Therefore, the contribution of this paper is that it provides a modeling framework in which the relevant tradeoffs between depositions and abatement costs for each of the 27 European countries can be analyzed interactively. Therefore, the model can serve as a decision support component in the process of establishing international environmental policies.

The remainder of the paper is organized as follows. First, the background of the acid rain problem and the RAINS model are discussed, followed by a presentation of the formal model formulation and the multicriteria decision support method. Next, our proposed model is illustrated by analyzing several scenarios and tradeoffs. Some extensions of our analysis and model formulation are suggested. The paper concludes with some final remarks.

BACKGROUND

Recently, a growing body of literature on the policy aspects of acidification has developed. This research can be divided into three types.

The first type focuses on the costs and effects of certain specific emission reduction scenarios. For instance, Shaw, Amann and Schoepp (1988) compare a non-abatement scenario (also called official energy scenario) with among others a uniform 30 percent reduction scenario by 1993 at the latest, which scenario was considered in the SO₂ protocol of Helsinki 1985 (Hettelingh and Hordijk 1987, p.39), and with current reduction plans as declared by the various countries. Shaw (1988) calculates costs associated with a uniform 50 percent emission reduction and shows how depositions could further be decreased by allocating the costs across countries in an optimal way in the sense that the total costs are minimized. This allocation of costs would involve a significant transfer of funds from Western European countries to Eastern European countries. Cesar and Klaassen (1989) estimate the deposition reductions and costs of the EC-directive (EEG 1988) on large combustion plants. One drawback of the above studies is that no interactive mechanism is used to evaluate alternative deposition and abatement cost levels. This makes "what-if" type analyses difficult, so that the tradeoffs between various scenarios cannot easily be evaluated. In addition, these papers often stress the advantages of coordinated international actions using major transfers of funds from West to East (Shaw 1988). In reality, the scope of such transfers may be very limited.

The second type of research emphasizes the welfare economic analysis of acid rain abatement (Maeler 1989; Van Ierland 1989). The distinguishing characteristic of this research is that costs of emission reductions as well as benefits of the corresponding improvement of ecosystems, materials and buildings are assessed in monetary terms. In particular for the benefits this is a cumbersome and controversial task, because the diversity of benefit components are difficult to express monetarily, and monetary benefits cannot easily be aggregated for all European countries. Maeler deals with this problem by assuming that marginal benefits are constant, and that the cost functions and expenditures are known. Assuming rational governments, he assesses the appropriate levels of costs and benefits by equating marginal costs and benefits. The assumption of constant marginal benefits, however, is questionable. Van Ierland, on the other hand, uses an estimated piecewise linear benefit function for the Federal Republic of Germany (FRG). In order to simplify the problem, he subsequently assumes the shape and values of the benefit functions for all other countries to be the same as for the FRG. It is obvious that an analysis in which deposition reductions are expressed in physical terms is preferred to the approach in the above studies where benefit functions are estimated in monetary values.

The third type of research focuses on policy implications, using either upper bounds or target values for the deposition levels in the various countries. We mention two studies in this class. Van Ierland (1989) deals with the ecologically oriented critical loads approach. The critical load represents the highest level of acidification for which no major damage is done to the ecosystem in the long run. Looking at both sulphur and nitrogen, Van

Ierland selects a critical load level of 1400 acid equivalents per hectare in his analysis. Klaassen and Jansen (1989) build a model using the political target approach. Concentrating on sulphur only, they take a target load of 3 grams of sulphur per square meter, which translates into approximately 1900 acid equivalents per hectare. A target load can be interpreted as an attainable and politically acceptable load for the intermediate term, the ultimate goal of course being the achievement of the critical loads. Given these loads, the costs and emission reductions needed to achieve these goals are calculated. As was the case with the first type of research, however, a drawback of these studies is that there is neither an explicit balancing of the tradeoffs between abatement costs and the benefits of corresponding lower depositions across countries, nor a user interactive tradeoff analysis.

This paper extends the above types of research by concentrating on an interactive analysis of tradeoffs between deposition reduction and abatement costs across all 27 countries. It is clear that such an analysis is of a multicriteria nature. The powerful and interactive nonlinear multicriteria optimization package IAC-DIDAS-N (Kreglewski, Paczynski, Granat and Wierzbicki 1988), also known as DIDAS-N, is used to perform this analysis. The analysis is performed without making the controversial step of trying to monetarize the benefits. Additionally, the advantages of cooperative action are stressed because the tradeoff analysis clearly indicates which countries might transfer limited amounts of funds to other countries. At the same time, by selecting reasonable ranges for the acceptable deposition levels and costs in the tradeoff analysis, the resulting solutions are such that none of the countries is assumed or required to pay unreasonable sums of money to other countries or to pay unreasonable domestic abatement costs.

THE RAINS MODEL

Before introducing the interactive decision support framework and the underlying model formulation, we briefly discuss the RAINS model which provides the cost estimates and the relevant air pollution transportation matrix. RAINS is an integrated model of acidification in Europe which describes the set of relations that link the generation of pollutants with their depositions, and thus with their adverse impacts on natural resources such as forests, groundwater and lakes. The emphasis of RAINS is on the transboundary aspects of air pollution (Alcamo et al. 1987). The model was developed at the International Institute for Applied Systems Analysis (IIASA) as a tool for evaluating control strategies. Currently the model is primarily sulphur-based, but nitrogen is presently being included and ammonia emissions may be included in the near future. The RAINS model can be run on an IBM/PC/XT/AT or compatible microcomputer.

The parts of the model relevant for the purpose of this paper are the Energy Pathway, SO₂ Emissions, SO₂ Transport (including deposition), and SO₂ Control and Abatement Costs. In the Energy Pathway and SO₂ emissions submodels, different energy projections can be implemented. The submodel accounts for five emission-producing sectors: conversion (e.g., refineries), power plants, domestic, industrial and transportation. Eight fuel types are distinguished: brown coal, hard coal, derived coal (e.g., coke, brown coal briquettes), light oil (e.g., gasoline), medium distillate (gas oil), heavy oil, gas and other fuels (Alcamo et al. 1987). The latter two are assumed to produce no sulphur emissions. Process emissions are taken into account as well when calculating the total emissions.

Energy conservation, fuel substitution, the use of lower sulphur fuels and desulphurization are considered as means of emission reduction in the Pollution Control and Costs submodels of RAINS. Combustion modification, flue gas desulphurization and regenerative processes are considered as feasible technologies for desulphurization. Energy conservation is not yet included in the costs submodel of RAINS. Costs are based on country- and technology-specific parameters (Amann et al. 1987). The resulting cost coefficients incorporate the most important factors influencing abatement costs of the European countries in an internationally comparable way. The cost functions are piecewise linear, reflecting that in order to reduce emissions further, another technique may have to be applied with higher marginal abatement costs.

The Transport submodel divides Europe into about 700 150x150 kilometer grids, and predicts sulphur concentration and deposition due to SO₂ emission patterns on each of these grids. In doing so, the submodel uses source-receptor linkages from the long range atmospheric transport model, developed by the Norwegian Meteorological Institute under the European Monitoring and Evaluation Program (EMEP) of the Economic Council of Europe (ECE) Convention on Transboundary Air Pollution. These source-receptor linkages combined determine the pollution transportation matrix.

In the following, a simplified version of RAINS, due to Maeler (1989), is used. This simplification is a modification of RAINS in two respects. First, quadratic approximations are made of the stepwise linear cost functions of RAINS. Second, an aggregated 27x27 transportation matrix, representing the sulphur transport between 27 European countries is used, rather than the 150x150 kilometer grids in the full-blown RAINS model. An advantage of this aggregation is that the tradeoff analysis is more straightforward. A disadvantage, however, is that the deposition levels in the aggregate model represent country-wide averages, so that the deposition effects on different ecosystems within a country cannot be analyzed explicitly. For a more detailed discussion of this simplified version and its drawbacks, the reader is referred to Maeler (1989).

The output from the above submodels of RAINS serves as the input for the decision support model in which the interactive tradeoff analysis is conducted. It is possible to evaluate multiple scenarios generated using RAINS within the decision support framework. In the illustration below, one such scenario based on Maeler (1989) is used.

MODEL FORMULATION

To determine the tradeoffs between the deposition levels and abatement costs for each country, the transboundary relationships between SO₂ emission, SO₂ emission reduction, deposition of acid rain, and the associated domestic abatement costs for each of the 27 countries can formally be stated as a nonlinear multicriteria mathematical programming problem. All monetary cost figures, emission data and deposition data in the remainder of this paper have been calculated on an annual basis. Denoting the surface of country *i* (in 1,000 square kilometers) by s_i and the deposition in country *i* (in 1,000 tons) by d_i , the decision problem for country *i* is by how much it should reduce its emissions (r_i) in such a way that both domestic abatement costs $c_i(r_i)$ and depositions in tons per square kilometer (or equivalently in grams per square meter) in country *i* (d_i/s_i) are at an acceptable level. At the same time, depositions in country *i* are affected by emission reductions in other countries. As *ceteris paribus* lower abatement costs and deposition levels are preferred to higher levels, the two criteria for country *i* are to minimize $z_{i1} = c_i(r_i)$ and $z_{i2} = d_i/s_i$. Therefore, the aggregate problem has a total of $27 \times 2 = 54$ separate criteria. Suppose we define the set of the 27 European countries by *S*. Then the mathematical formulation of the problem is as follows.

$$\text{Minimize } z_{i1} = c_i(r_i) \quad \text{for all } i \in S \quad (1)$$

$$\text{Minimize } z_{i2} = d_i/s_i \quad \text{for all } i \in S \quad (2)$$

Subject to:

$$d_i = \sum_j a_{ij} * (e_j - r_j) \quad \text{for all } i \in S \quad (3)$$

$$0 \leq r_i \leq m_i * e_i \quad \text{for all } i \in S \quad (4)$$

where $A = \{a_{ij}\}$ is the 27×27 SO₂ transportation matrix between the different countries, such that a_{ij} is the deposition in country *i* as a percentage of SO₂ emissions in country *j*; e_i represents the initial SO₂ emission by country *i* (in 1,000 tons), i.e. the current emission level if a non-abatement strategy is adopted; and m_i represents the maximum technologically feasible emission reduction for country *i* as a percentage of e_i . Maeler (1989,p.14) indicates that the data on m_i are based on information from IIASA. As mentioned before, following Maeler quadratic abatement cost functions of the form $c_i(r_i) = \alpha_i r_i + \beta_i r_i^2$ are used, where α_i and β_i are scalar coefficients. The cost function estimates

are based on the Energy Scenario 2000, and are expressed in million D-Marks. The emission and deposition data are based on 1984 energy consumption patterns (Maeler 1989, p.14). The relevant numerical data for our illustration are summarized in Tables 1 and 2. The SO₂ transportation matrix in Table 2 is adapted from Maeler (1989).

Table 1: Relevant Information on the 27 European Countries

Country Name (i)	Abbreviation	Current Emissions (1,000 tons) (e _i)	Maximum Reduction (%) (m _i)	GNP (10 ⁶ US\$) (g _i)	Surface (1000 km ²) (s _i)	Cost Coefficients	
						Linear (α _i)	Quadratic (β _i)
Albania	ALB	25	78	NA	29	1.25	.026
Austria	AUS	147	77	70,640	84	1.00	.020
Belgium	BEL	306	67	109,640	31	2.00	.0095
Bulgaria	BUL	500	83	37,390	111	1.40	.0021
Czechoslovakia	CZE	1,625	75	89,260	128	1.00	.000283
Denmark	DEN	151	86	61,520	43	1.80	.0054
Finland	FIN	180	85	46,360	337	1.00	.0175
France	FRA	1,015	76	601,560	547	2.00	.0054
German Dem.Rep.	GDR	1,300	80	120,940	249	1.00	.0005
Fed.Rep. Germany	FRG	1,375	86	758,480	108	2.00	.00056
Greece	GRE	352	86	39,910	132	0.831	.0000
Hungary	HUN	825	77	20,650	93	0.60	.000389
Ireland	IRE	70	82	16,300	70	1.25	.0100
Italy	ITA	1,900	84	359,210	301	1.05	.0006
Luxembourg	LUX	14	90	5,400	3	7.00	.6000
Netherlands	NET	170	87	155,740	41	2.50	.0076
Norway	NOR	50	73	52,410	324	1.75	.14627
Poland	POL	2,050	63	139,780	313	0.85	.000849
Portugal	POR	79	89	22,430	92	1.35	.006196
Romania	ROM	100	83	50,870	238	1.15	.000543
Spain	SPA	1,638	82	195,670	505	0.50	.000668
Sweden	SWE	165	76	114,150	450	2.50	.05927
Switzerland	SWI	43	55	101,440	41	2.00	.07133
Turkey	TUR	483	62	61,610	461	1.25	.000555
Soviet Union	USS	6,000	76	1,212,030	3,364	1.30	.000141
United Kingdom	UNK	1,845	81	467,880	244	1.30	.000193
Yugoslavia	YUG	588	79	56,660	256	1.25	.000483

In addition to the above model restrictions, we will use policy target levels which seek to limit the abatement costs $c_i(r_i)$ of country i to a specific percentage p_i of the annual GNP of country i , g_i . The reference point method upon which the multicriteria decision support package DIDAS-N is based, is well-suited for utilizing such policy target levels in the form of aspiration levels and reservation levels for each of the criteria. The DIDAS-N methodology is presented next.

Table 2: SO₂ Pollution Transportation Matrix for the 27 European Countries

from to	ALB	AUS	BEL	BUL	CZE	DEN	FIN	FRA	GDR	FRG	GRE	HUN	IRE	ITA	LUX	NET	NOR	POL	POR	ROM	SPA	SWE	SWI	TUR	USS	UNK	YUG	
ALB	.24			.01							.01																	
AUS		.26	.01		.02			.01	.01	.01		.02		.02				.01					.04					.02
BEL			.20					.02		.01					.02	.02											.01	
BUL	.01			.30							.01	.01									.04			.01				.01
CZE		.06	.01		.26	.01		.01	.04	.02		.06		.01		.01		.04			.01		.01					.02
DEN						.20			.01	.01												.01						
FIN						.01	.33										.02					.04			.01			
FRA		.01	.08		.01	.01		.35	.01	.04			.02	.03	.13	.04			.01		.04		.08				.03	.01
GDR		.01	.02		.05	.02		.01	.27	.05						.02		.01									.01	
FRG		.04	.09		.03	.02		.06	.05	.31		.01	.01	.01	.14	.09		.01				.01	.07				.02	.01
GRE	.05			.04							.26										.01			.01				.01
HUN		.04			.02				.01			.27		.01				.01		.02								.05
IRE													.24														.01	
ITA	.02	.03		.01	.01			.02		.01		.01		.35							.01		.07					.03
LUX															.14													
NET			.05					.01		.03						.22												.01
NOR			.01			.03	.01		.01	.01						.01	.28					.03						.01
POL		.03	.02		.10	.03		.01	.11	.04		.04		.01		.02				.34	.01		.01	.01			.01	.01
POR																			.27		.01	.01						.01
ROM		.01		.05	.02				.01			.07		.01						.02		.35		.01				.05
SPA								.02		.01									.08		.32		.01					
SWE			.01		.01	.07	.04		.02	.02						.01	.09	.01				.32						.01
SWI		.01						.01		.01				.02									.26					
TUR	.01			.04							.03										.01				.33			.01
USS	.02	.04	.02	.05	.08	.07	.15	.01	.07	.04	.02	.09	.01	.01		.03	.04	.14		.14		.08	.01	.03	.40	.02	.04	
UNK			.02			.01		.01		.01			.07			.02											.28	
YUG	.06	.05		.06	.01			.01	.01	.01	.02	.06		.04						.01	.03		.01					.35

MULTICRITERIA METHODOLOGY

The nonlinear multicriteria system DIDAS-N 3.2 (Kreglewski, Paczynski, Granat and Wierzbicki 1988) can be run on an IBM/PC/XT/AT or compatible computer, so that the computer environment is the same as for the RAINS model. DIDAS-N uses a user-friendly spreadsheet format, and facilitates an interactive decision process which is based on the reference point method (Wierzbicki 1982, Lewandowski and Wierzbicki 1988a, 1988b). The methodology underlying DIDAS-N uses the concepts of satisficing solutions and bounded rationality (March and Simon 1958), and has been shown to be consistent with the process of human decision making.

At each stage of the interactive process, the decision maker can specify aspiration and reservation levels for the criteria. The aspiration level of a criterion represents the level which the decision maker would like to achieve, if possible, and the reservation level is the worst level acceptable to the decision maker. The aspiration and reservation levels are also called reference points. DIDAS-N uses these specified reference point values as the basis for solving a multicriteria optimization problem to find a Pareto optimal or nondominated solution which reaches the aspiration levels of the criteria as closely as possible, while satisfying the reservation levels for the criteria, if possible. A solution is Pareto optimal if none of the criteria can be improved without sacrificing at least one of the remaining criteria. A detailed discussion of the reference point method can be found in Wierzbicki (1982) or the user manual of DIDAS-N (Kreglewski, Paczynski, Granat and Wierzbicki 1988). For other more general overviews of multicriteria decision making techniques and concepts the interested reader is referred to Steuer (1986) and Yu (1985).

At each iteration, the solution which is calculated using the specified aspiration and reservation levels of the criteria is presented to the decision maker, who can subsequently modify these levels according to his preferences and the information contained in the solution. In this way he is able to interactively explore various tradeoffs between the criteria. For instance, if the decision maker wishes to improve the deposition level in a given country, he can lower the aspiration or reservation level for this criterion (or both), and within the ranges of all other criteria the model will attempt to find a solution which reaches the aspiration level as much as possible. At any point of the analysis the decision maker can inspect and evaluate the relevant decision variables on the screen. It is also possible to graphically display the tradeoffs between the criteria in the form of bargraphs.

Using the model formulation in (1) through (4), DIDAS-N first calculates the utopia and nadir values for the deposition and abatement cost criteria for each country. The utopia or selfish value of a criterion is its best possible value, ignoring all other criteria. Since the different criteria are conflicting, it is typically not possible to simultaneously attain the utopia values for all criteria. The nadir value of a criterion is defined by its worst possible value over the set of Pareto optimal solutions. It is very difficult to calculate the exact nadir values, so that DIDAS-N approximates them by the worst criteria values calculated during the analysis. The utopia and nadir values provide important information to the decision maker, because they define the relevant range of criteria values which should be considered in the tradeoff analysis. For instance, if the utopia value for deposition in France equals 0.29 grams per square meter, then it is unreasonable - within the structure and underlying assumptions of the current model - to strive for deposition levels of less than 0.29 grams per square meter. An illustration of the methodology follows next.

ILLUSTRATION

The utopia and nadir values for all 27 countries are given in Table 3. This table also shows the initial "neutral" solution and associated initial aspiration (Asp) and reservation (Res) levels which DIDAS-N suggests as a reasonable starting point for the interactive decision process. Before continuing the tradeoff analysis, we examine the results in Table 3 in more detail. It is clear that the utopia value for abatement costs $c_i(r_i)$ equals zero for each country, because the lowest possible costs are associated with the non-abatement strategy ($r_i = 0$). On the other hand, the cost functions are convex, so that the nadir value for abatement costs (c_i^N) is found by reducing domestic emissions to the maximum technologically feasible extent, implying $r_i = m_i * e_i$ and thus $c_i^N(r_i) = c_i(m_i * e_i)$. For instance, the maximum emission reduction for Ireland is $r_{IRE} = 0.82 * 70 = 57.4$ (see Table 1), so that its nadir cost value is $c_{IRE}^N = 1.25 * 57.4 + 0.01 * (57.4)^2 = 104.7$ million D-Mark. Similarly, the nadir value for deposition in each country is associated with the status quo of non-abatement, while the utopia value is reached if each country reduces emissions maximally. Again taking Ireland as an example, the SO_2 transportation matrix in Table 2 shows that $d_{IRE} = 0.24 * e_{IRE} + 0.01 * e_{UNK}$. Non-abatement would imply $d_{IRE} = 0.24 * 70 + 0.01 * 1,845 = 35.25$, so that the deposition in grams per square meter is given by $d_{IRE}/s_{IRE} = 35.25/70 = 0.50$, while the maximum abatement strategy would yield $d_{IRE}/s_{IRE} = (0.24 * (1 - 0.82) * 70 + 0.01 * (1 - 0.81) * 1,845)/70 = 0.09$. These values can also be found in Table 3.

Table 3: Utopia, Nadir Values, Aspiration, Reservation Values for the Initial (Neutral) Solution for the Unrestricted Model, All 27 Countries

Country	Costs (million D-Mark)					Deposition (grams/m ²)				
	Utopia	Asp	Solution	Res	Nadir	Utopia	Asp	Solution	Res	Nadir
ALB	0	9.8	14.8	19.7	34.3	0.09	0.22	0.29	0.35	0.50
AUS	0	89.4	134.1	178.8	369.4	0.54	1.10	1.38	1.66	2.37
BEL	0	223.0	334.4	445.9	809.2	1.00	1.86	2.28	2.71	3.79
BUL	0	298.2	447.3	596.5	942.7	0.29	0.67	0.87	1.06	1.59
CZE	0	471.7	707.6	943.5	1,639.5	1.37	2.65	3.30	3.94	5.40
DEN	0	89.4	134.1	178.8	324.9	0.22	0.58	0.76	0.94	1.40
FIN	0	134.5	201.8	269.0	562.7	0.08	0.16	0.21	0.25	0.38
FRA	0	1,094.3	1,641.5	2,188.7	4,756.1	0.29	0.57	0.71	0.85	1.22
GDR	0	130.0	195.0	260.0	540.8	1.10	2.24	2.81	3.39	5.22
FRG	0	207.6	311.4	415.2	783.7	0.57	1.23	1.55	1.88	3.01
GRE	0	82.0	123.1	164.1	251.5	0.15	0.41	0.55	0.68	0.94
HUN	0	159.9	239.8	319.7	538.2	0.86	1.78	2.23	2.69	3.71
IRE	0	30.7	46.0	61.3	104.7	0.09	0.23	0.29	0.36	0.50
ITA	0	958.7	1,438.1	1,917.4	3,204.1	0.45	1.06	1.36	1.67	2.56
LUX	0	53.0	79.5	106.0	183.5	0.07	0.24	0.32	0.41	0.65
NET	0	139.1	208.7	278.2	536.0	0.53	1.28	1.66	2.03	2.99
NOR	0	52.2	78.4	104.5	258.7	0.06	0.11	0.13	0.15	0.23
POL	0	681.3	1,022.0	1,362.7	2,515.4	1.17	1.93	2.31	2.69	3.72
POR	0	36.9	55.3	73.8	125.5	0.06	0.17	0.23	0.28	0.41
ROM	0	25.1	37.7	50.2	99.2	0.27	0.53	0.67	0.80	1.09
SPA	0	48.4	72.6	96.8	1,876.3	0.20	0.48	0.62	0.76	1.12
SWE	0	276.1	414.2	552.3	1,245.5	0.11	0.20	0.24	0.29	0.42
SWI	0	18.1	27.1	36.2	87.2	0.39	0.81	1.02	1.23	1.82
TUR	0	132.6	198.8	265.1	424.2	0.15	0.24	0.28	0.33	0.43
USS	0	3,093.4	4,640.1	6,186.8	8,859.9	0.22	0.42	0.51	0.61	0.92
UNK	0	739.7	1,109.5	1,479.4	2,373.0	0.44	1.03	1.33	1.62	2.28
YUG	0	196.2	294.2	392.3	684.8	0.41	0.84	1.05	1.27	1.77

In the initial solution, throughout Europe abatement costs are quite low compared to their nadir values. Most deposition levels are at a moderate level, with the exception of Belgium, Czechoslovakia, the German Democratic Republic (GDR), Hungary and Poland. These countries have a deposition level of more than 2 grams per square meter. The deposition of 3.30 grams in Czechoslovakia is particularly high, considering that this level represents a country-wide average, so that certain parts of the country will have much higher pollution levels. The model in Table 3 is called the "unrestricted" model, because no "hard" constraints are used to limit abatement costs and deposition levels.

As a first step to achieve deposition and cost levels within reasonable margins, the reservation levels suggested in the initial solution were uniformly changed to 2 grams per square meter for deposition and to 0.4 percent of GNP for abatement costs. None of the aspiration levels were changed. The GNP figures in Table 1 are in U.S. dollars, and the cost functions are expressed in D-Marks. For the purpose of our analysis, the GNP data were converted to D-Marks using a conversion rate of 2.5 D-Marks for 1 U.S. dollar. Of course conversion rates fluctuate considerably, so that this rate is not exactly correct. In our paper

the GNP data are only used for establishing reservation levels for abatement costs, so that a rough estimate of the conversion rate suffices. It is easy to repeat the analysis in our illustration using a different conversion rate, if this is desired. Since the reservation levels for all countries will be affected in the same proportion, the resulting solutions will likely be similar. Simply stated, the reservation level of 2 grams for the average deposition within each country can be viewed as a pollution load, above which the ecosystem would be badly disturbed. The purpose of selecting these reservation levels is to study how this deposition level of one country can be reached by additional emission reduction measures in another country, especially if this one country already has high abatement costs. The modified solution presented by DIDAS-N is given in Table 4.

Table 4: Suggested Solution with Uniform Reservation levels, Unrestricted Model

Country	Costs (million D-Mark)			Deposition (grams/m ²)		
	Aspiration	Solution	Reservation	Aspiration	Solution	Reservation
ALB	0	0.0	34.3	0.09	0.46	2.00
AUS	0	369.4	706.4	0.54	0.74	2.00
BEL	0	809.2	1,096.0	1.00	1.20	2.00
BUL	0	173.6	373.9	0.29	1.21	2.00
CZE	0	1,211.2*	892.6	1.37	2.17*	2.00
DEN	0	324.9	615.2	0.22	0.24	2.00
FIN	0	0.0	463.6	0.08	0.31	2.00
FRA	0	4,756.1	6,015.6	0.29	0.40	2.00
GDR	0	540.8	1,209.4	1.10	1.29	2.00
FRG	0	783.7	7,584.8	0.57	0.67	2.00
GRE	0	0.0	399.1	0.15	0.88	2.00
HUN	0	222.2*	206.5	0.86	1.95	2.00
IRE	0	0.0	163.0	0.09	0.38	2.00
ITA	0	3,204.1	3,592.0	0.45	0.51	2.00
LUX	0	0.0	54.0	0.07	0.65	2.00
NET	0	536.0	1,557.0	0.53	0.68	2.00
NOR	0	0.7	524.1	0.06	0.11	2.00
POL	0	1,540.6*	1,397.8	1.17	1.68	2.00
POR	0	0.0	224.3	0.06	0.40	2.00
ROM	0	99.2	508.7	0.27	0.50	2.00
SPA	0	25.9	1,956.7	0.20	1.03	2.00
SWE	0	199.6	1,141.5	0.11	0.20	2.00
SWI	0	87.2	1,014.4	0.39	0.39	2.00
TUR	0	0.0	616.1	0.15	0.41	2.00
USS	0	3,267.4	12,120.3	0.22	0.56	2.00
UNK	0	1,305.3	4,678.8	0.44	1.15	2.00
YUG	0	554.8	566.6	0.41	0.68	2.00

*: The reservation level could not be attained for this country, using the current scenario.

For several countries, the deposition and cost reservation levels could not be met. In the case of Czechoslovakia, both the deposition and cost reservation levels were not met, but the nadir value for abatement costs was not yet reached, so that this country could reduce its domestic depositions further, albeit at a great expense. Later we will address this issue in more detail. Countries such as Belgium, Hungary, the GDR and Poland, which had high deposition levels in the initial solution (see Table 3) now have greatly reduced deposition

levels, but in the case of Poland at a cost exceeding the target level of 0.4 percent of GNP. In Table 4, Hungary has a reduced deposition level in spite of slightly lower domestic emission reductions than in the initial solution in Table 3. This is due to the increased emission abatement activities in surrounding countries. The reason why Hungary itself does not spend additional funds on abatement is that the current level in Table 4, 222.2 million D-Mark, already exceeds its reservation level of 0.4 percent of GNP, 206.5 million D-Mark.

Interestingly, a number of Western European countries (e.g., FRG, Belgium, Denmark, France, Italy and the Netherlands) are at their nadir cost levels in Table 4, so that these countries are reducing their domestic emissions to the maximum feasible extent. The reason is that for these countries the 0.4 percent of GNP, used as the reservation level for abatement costs, far exceeds the nadir cost values. Thus, given the 0.4 percent reservation level, it is reasonable to assume that these countries might be willing to transfer limited funds to other countries which have not yet reached their technological emission reduction limits, but have already exceeded their cost reservation levels.

As a further exercise, we divided Europe into Eastern Europe (the COMECON countries, Albania, Turkey and Yugoslavia) and Western Europe (The European Community, the Nordic countries, Austria and Switzerland). The deposition reservation levels for the Eastern European countries were kept at 2 grams per square meter, but for the Western countries these levels were tightened to 1 gram. The latter level of 1 gram comes closer to the actual critical load. At the same time, in order to obtain more realistic results the reservation levels for abatement costs were lowered from 0.4 percent to 0.2 percent of GNP for Eastern Europe. The levels for the Western countries were kept at 0.4 percent. Table 5 has the revised solution.

In four Eastern European countries (Czechoslovakia, Hungary, Poland and Yugoslavia) and in Luxembourg, the cost targets were not met, and in addition the deposition level of 2 grams was not reached in Czechoslovakia and Hungary. Comparing Tables 4 and 5, we see that relaxing the reservation levels for abatement costs leads the Eastern European countries to spend less money on emission reduction, and as a result depositions are generally higher in Table 5. On the other hand, many of the Western European countries were already spending relatively high amounts of money in the solution of Table 4, and spend even more in that of Table 5, in order to reach the tighter deposition reservation level of 1 gram per square meter. A good example of this increased effort is the case of Luxembourg, which spends little money under the 2 gram scenario, but spends 123.4 million D-Mark in the 1 gram scenario. In fact, this additional expense is a sacrifice by Luxembourg to aid Belgium in reducing its deposition level from 1.20 in Table 4 to 1.0. Note that Belgium itself cannot spend more than it is already doing (809.2 million D-Mark). If such a sacrifice by

Luxembourg is considered unreasonable, the model can easily be modified to set a limit to the sacrifice by Luxembourg. In our illustration this was not done.

Table 5: Suggested Solution with Different Reservation Levels for Eastern and Western Europe, Unrestricted Model

Country	Costs (million D-Mark)			Deposition (grams/m ²)		
	Aspiration	Solution	Reservation	Aspiration	Solution	Reservation
ALB	0	12.0	34.3	0.09	0.38	2.00
AUS	0	369.4	706.4	0.54	0.85	1.00
BEL	0	809.2	1,096.4	1.00	1.00	1.00
BUL	0	96.2	187.0	0.29	1.34	2.00
CZE	0	917.0*	446.3	1.37	2.67*	2.00
DEN	0	324.9	615.2	0.22	0.24	1.00
FIN	0	0.0	463.6	0.08	0.31	1.00
FRA	0	4,756.1	6,015.6	0.29	0.35	1.00
GDR	0	540.8	604.7	1.10	1.34	2.00
FRG	0	783.7	7,584.8	0.57	0.65	1.00
GRE	0	78.9	399.1	0.15	0.71	1.00
HUN	0	164.3*	103.3	0.86	2.27*	2.00
IRE	0	0.0	163.0	0.09	0.29	1.00
ITA	0	3,204.1	3,592.1	0.45	0.52	1.00
LUX	0	123.4*	54.0	0.07	0.20	1.00
NET	0	536.0	1,557.4	0.53	0.53	1.00
NOR	0	0.0	524.1	0.06	0.09	1.00
POL	0	1,170.6*	698.9	1.17	1.91	2.00
POR	0	98.8	224.3	0.06	0.21	1.00
ROM	0	99.2	254.4	0.27	0.58	2.00
SPA	0	205.2	1,956.7	0.20	0.87	1.00
SWE	0	225.6	1,141.5	0.11	0.19	1.00
SWI	0	87.2	1,014.4	0.39	0.39	1.00
TUR	0	0.1	308.1	0.15	0.41	2.00
USS	0	3,259.0	6,060.2	0.22	0.57	2.00
UNK	0	2,373.0	4,678.8	0.44	0.45	1.00
YUG	0	413.6*	283.3	0.41	0.83	2.00

*: The reservation level could not be attained for this country, using the current scenario.

It is of interest to see whether it is possible (feasible) to impose a "hard" restriction of at most 2 grams per square meter on the deposition level in each country. Such a hard restriction (upper bound) differs from a reservation level in that reservation levels do not have to be reached at any price, but no feasible solution exists if an upper bound cannot be satisfied, and the mathematical program cannot be solved without relaxing some of these bounds. Table 6 gives the results from solving the revised model with uniform reservation levels of 2 grams for deposition and 0.4 percent of GNP for abatement costs. We call this the "restricted" model because of the "hard" constraints mentioned above.

Due to imposing the upper bounds, the utopia values for the criteria in Table 6 are slightly different from the previous Tables. In particular, the lowest feasible abatement costs for Czechoslovakia, the GDR, Hungary and Poland are considerable. As expected, all deposition levels in the solution of Table 6 are now at most 2 grams per square meter, and

Czechoslovakia is the only country which is exactly at its upper bound. Note that the surrounding countries are forced to major expenditures in order to force the deposition level in Czechoslovakia down to 2 grams. Czechoslovakia itself, however, is not spending more in the restricted solution of Table 6 than in its unrestricted counterpart of Table 5, because it was already spending considerably in excess of its reservation level 892.6 million D-Mark. Similar to the situation described above for Luxembourg in Table 5, if it is deemed appropriate for Czechoslovakia to spend more on reducing its domestic emission, either its abatement cost reservation level can be increased or a "hard" lower bound on its abatement expenditures can be imposed.

Table 6: Suggested Solution with Uniform Reservation Levels for All 27 European Countries, Restricted Model

Country	Costs (million D-Mark)			Deposition (grams/m ²)		
	Aspiration	Solution	Reservation	Aspiration	Solution	Reservation
ALB	0	3.1	34.3	0.34	0.41	2.00
AUS	0	369.4	706.4	0.69	0.74	2.00
BEL	0	809.2	1,096.4	1.04	1.18	2.00
BUL	0	192.2	373.9	0.83	1.16	2.00
CZE	1,185.1	1,185.1*	892.6	1.63	2.00	2.00
DEN	0	324.9	615.2	0.22	0.24	2.00
FIN	0	92.5	463.6	0.24	0.24	2.00
FRA	0	4,502.9	6,015.6	0.33	0.38	2.00
GDR	210.3	540.8	1,209.4	1.17	1.26	2.00
FRG	0	783.7	7,584.8	0.60	0.66	2.00
GRE	0	79.0	399.1	0.61	0.67	2.00
HUN	184.0	249.7*	206.5	0.96	1.80	2.00
IRE	0	2.1	163.0	0.15	0.36	2.00
ITA	0	2,556.7	3,592.1	0.67	0.75	2.00
LUX	0	9.0	54.0	0.07	0.60	2.00
NET	0	536.0	1,557.4	0.56	0.66	2.00
NOR	0	2.6	524.1	0.09	0.09	2.00
POL	581.6	2,515.4*	1,397.8	1.26	1.30	2.00
POR	0	0.1	224.3	0.30	0.33	2.00
ROM	0	99.2	508.7	0.34	0.45	2.00
SPA	0	708.8	1,956.7	0.60	0.61	2.00
SWE	0	95.9	1,141.5	0.13	0.19	2.00
SWI	0	87.2	1,014.4	0.48	0.50	2.00
TUR	0	96.0	616.1	0.33	0.35	2.00
USS	0	4,607.5	12,120.3	0.46	0.46	2.00
UNK	0	1,478.3	4,678.8	0.47	1.03	2.00
YUG	0	684.8*	566.6	0.50	0.58	2.00

*: The reservation level could not be attained for this country, using the current scenario.

The restricted model with "hard" upper bounds of 2 grams for depositions in each country was also re-solved using the scenario of Table 5 with different reservation levels for Eastern (2 grams, 0.2 percent of GNP) and Western (1 gram, 0.4 percent of GNP) European countries. The results in Table 7 show that two countries, Belgium and Czechoslovakia, are exactly at the upper bound of their deposition level. Comparing Table 7 with Table 5, we

see that the deposition reduction from 2.67 to 2.0 grams in Czechoslovakia is in part due to a considerable abatement increase by Poland.

Table 7: Suggested Solution with Different Reservation Levels for Eastern and Western Europe, Restricted Model

Country	Costs (million D-Mark)			Deposition (grams/m ²)		
	Aspiration	Solution	Reservation	Aspiration	Solution	Reservation
ALB	0	12.9	34.3	0.34	0.38	2.00
AUS	0	369.4	706.4	0.69	0.69	1.00
BEL	83.5	809.2	1,096.4	1.04	1.00	1.00
BUL	0	342.7*	187.0	0.83	1.42	2.00
CZE	1,185.1	1,207.1*	446.3	1.63	2.00	2.00
DEN	0	324.9	615.2	0.22	0.24	1.00
FIN	0	34.3	463.6	0.24	0.27	1.00
FRA	0	4,706.1	6,015.6	0.33	0.32	1.00
GDR	210.3	540.8	604.7	1.17	1.21	2.00
FRG	0	783.7	7,584.8	0.60	0.60	1.00
GRE	0	87.8	399.1	0.61	0.68	1.00
HUN	184.0	195.1*	103.3	0.96	1.97	2.00
IRE	0	7.3	163.0	0.15	0.27	1.00
ITA	0	3,204.1	3,592.1	0.67	0.48	1.00
LUX	0	9.8	54.0	0.07	0.59	1.00
NET	0	536.0	1,557.4	0.56	0.53	1.00
NOR	0	1.6	524.1	0.09	0.09	1.00
POL	581.6	2,515.4*	698.9	1.26	1.28	2.00
POR	0	16.5	224.3	0.30	0.30	1.00
ROM	0	99.2	254.4	0.34	0.48	2.00
SPA	0	689.6	1,956.7	0.60	0.61	1.00
SWE	0	59.2	1,141.5	0.13	0.20	1.00
SWI	0	87.2	1,014.4	0.48	0.39	1.00
TUR	0	49.4	308.1	0.33	0.38	2.00
USS	0	4,578.0	6,060.2	0.46	0.46	2.00
UNK	0	2,334.6	4,678.8	0.47	0.47	1.00
YUG	0	684.8*	283.3	0.50	0.57	2.00

*: The reservation level could not be attained for this country, using the current scenario.

The above analyses show that a limited transfer of money from a country spending less than given target amount to a country spending more, might be reasonable. The extent of such transfers can be controlled by manipulating the aspiration and reservation levels for the criteria. These limited transfers are different from the transfers proposed by Maeler (1989) and by Bergman, Cesar and Klaassen (1989), in that our solutions suggest only few countries receive a payment and the amounts are much lower. A drawback of our solutions is that abatements are not always done in the most cost-efficient way. On the other hand, the smaller transfers involved may render the solutions more realistic.

As a last case we study the situation where Belgium and the Netherlands want to limit depositions to at most 1 gram. For the remaining 25 countries, the aspiration and reservation levels suggested in the initial "neutral" solution by DIDAS-N were used. The results for Belgium and the Netherlands from the initial "neutral" solution for the unrestricted model in Table 3 are repeated in Table 8. In this solution, the deposition levels suggested by DIDAS-N for Belgium (2.28 grams) and the Netherlands (1.66 grams) are rather high, and

the abatement costs are much below both the nadir values and the reservation level of 0.4 percent of GNP. Since in this section we want to focus on depositions, the aspiration and reservation levels for abatement costs were kept at the levels suggested by DIDAS-N in the initial solution. This implies that the reservation levels for abatement costs will be impossible to attain given our goal of lowering depositions.

From Table 9 we see that in the scenario where the aspiration and reservation levels for depositions in the Netherlands are set equal to 1 gram, both Belgium and the Netherlands spend more money on reducing emissions than in the "neutral" solution: 550.2 million D-Mark versus 334.4 million for Belgium, and 391.4 million versus 208.7 million for the Netherlands. Both these cost figures are at a moderate level compared to their nadir values of 809.2 and 536.0 million D-Mark, respectively. Table 10 shows the situation where the reference level for deposition in Belgium is set equal to 1 gram.

Table 8: Neutral Solution for Belgium and the Netherlands, Unrestricted Model

Country	Costs (million D-Mark)			Deposition (grams/m ²)		
	Aspiration	Solution	Reservation	Aspiration	Solution	Reservation
BEL	223.0	334.4	445.9	1.86	2.28	2.71
NET	139.1	208.7	278.2	1.28	1.66	2.03

Table 9: Suggested Solution for Belgium and the Netherlands, Deposition Reservation Level in the Netherlands Equal to One

Country	Costs (million D-Mark)			Deposition (grams/m ²)		
	Aspiration	Solution	Reservation	Aspiration	Solution	Reservation
BEL	223.0	550.2	445.9	1.86	1.62	2.71
NET	139.1	391.4	278.2	1.00	1.00	1.00

Table 10: Suggested Solution for Belgium and the Netherlands, Deposition Reservation Level in Belgium Equal to One

Country	Costs (million D-Mark)			Deposition (grams/m ²)		
	Aspiration	Solution	Reservation	Aspiration	Solution	Reservation
BEL	223.0	809.2	445.9	1.00	1.00	1.00
NET	139.1	534.6	278.2	0.13	0.53	2.03

As was noted before, Belgium has difficulties achieving such a deposition level without help from other countries. This is shown by its very high domestic abatement costs, equal to the

nadir value (809.2 million D-Mark). The Netherlands, on the other hand, helps Belgium by considerably reducing its emissions to 0.53 grams. The abatement costs to the Netherlands of 534.4 million D-Mark are quite high, and close to its nadir value of 536.0 million D-Mark. A reasonable conclusion is that perhaps Belgium might consider transferring a limited amount of money, not exceeding the differential effort by the Netherlands of $534.4 - 391.4 = 143.0$ million D-Mark, if Belgium insists on limiting its depositions to 1 gram per square meter. The extent of this transfer might be decided in international negotiations. Finally, Table 11 shows the results of setting the reference values for both Belgium and the Netherlands equal to 1 gram. Since the Netherlands have no problems attaining a deposition level below 1 gram, it is not surprising that the solution in Table 11 is very similar to that in Table 10.

Table 11: Suggested Solution for Belgium and the Netherlands, Deposition Reservation Level for Both Equal to One

Country	Costs (million D-Mark)			Deposition (grams/m ²)		
	Aspiration	Solution	Reservation	Aspiration	Solution	Reservation
BEL	223.0	809.2	445.9	1.00	1.00	1.00
NET	139.1	521.6	278.2	1.00	0.54	1.00

EXTENSIONS

The current model formulation can be extended in a number of ways. First, it is possible to focus on individual countries other than the ones selected in our illustration. Second, the model can easily be reformulated to consider blocks of countries with aggregate cost functions. Two such blocks which may be of interest are on the one hand the European Community, and on the other hand the COMECON countries. Game theoretic aspects of the model dynamics can be explored as well.

A straightforward extension of the current formulation is to include nitrogen emissions in the model, and to consider Ph-levels rather than depositions due to SO₂ emissions only. Such a model would involve a dynamic problem formulation, as the Ph-levels of the soil depend in part on the Ph-levels in the previous year. A pilot version of such a model formulation is already available as a demonstration problem on the DIDAS-N diskette (Kreglewski, Paczynski, Granat and Wierzbicki 1988, pp. 38-41). This example problem is of limited size (2 regions and 3 years), and is a simplified version of the model formulation by Hettelingh and Hordijk (1986).

Another extension would be to utilize a finer grid of source-receptor linkages in the analysis. The analysis in our current paper is very rough, because only information on country-wide average depositions was used. A finer grid would enable studying the effects of pollution on different ecosystems, and would enable the policy maker to establish tighter limits on those ecosystems which are particularly sensitive to pollution.

FINAL REMARKS

In this paper, a multicriteria framework was proposed to analyze tradeoffs between deposition levels and abatement costs within and across 27 European countries. The illustration clearly shows that it is possible to investigate numerous different scenarios where the criteria levels for various countries are restricted, using either "hard" constraints (upper bounds) or "soft" target values (aspiration and reservation levels). Rather than comprehensively analyzing policy and strategy issues, our purpose in the current paper was to emphasize these possibilities. The task of analyzing the pros and cons of different scenarios associated with the acid rain problem in Europe is a very complicated one. Our proposed methodology provides a useful decision support tool to aid policy makers in analyzing this problem. Of course our paper constitutes only a first attempt towards designing a true decision support framework, and much work is yet to be done along the lines of the extensions mentioned above.

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