A game-theoretic approach to pollution control problems

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ABSTRACT

This paper provides a model that attempts to deal with the transboundary nature of the acid rain problem, using a game theoretic approach consistent with mainstream economic theory. The general forms of cooperative and non-cooperative equilibria in the explicit and implicit set-up of the model are presented under the assumptions of deterministic and stochastic deposits.

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Introduction

Much has been written recently about the use of negotiation and bargaining to resolve environmental conflicts. Negotiation and bargaining occur between governments to attempt to settle conflicts concerning land use, energy and air quality (Bingham, 1986). Bargaining has generated much theoretical interest, beginning with the classic work of Nash (1950, 1953) and Raiffa (1953). Until a few years ago, most theoretical work assumed complete information, i.e. the bargainers' utility functions, the set of feasible agreements and the recourse options available if bargaining failed were all considered to be common knowledge. According to this assumption, the problem was explored using one of the following approaches:

i) The first approach was presented in Nash (1950, 1953) and Raiffa (1953) and was extended and completed recently by Roth (1979), has not tried to describe the bargaining process explicitly through a specific extensive form. Rather, it has concentrated on formulating and exploring the implications of general principles that are compatible with possibly many different extensive forms. This approach is often described as "cooperative" since the jointly agreed-upon solution is implemented presumably by a binding agreement (Roth, 1979).

ii) The second way of exploring the bargaining process specifies a bargaining game, whose equilibrium outcome then serves as a predictor of the outcome of the actual bargaining process. The Nash solution is only one of many equilibria of a simple one stage demand game in which players make demands simultaneously and the agreement occurs if the two demands can be met by a feasible agreement. If the demands are not compatible in this way, a conflict occurs and two possible disagreement outcomes can be considered:

    - the status quo which corresponds τo zero welfare improvements for each country and

- the non-cooperative Nash equilibrium i.e. the equilibrium point without any pre-play activity between the bargainers (Harrison and Rutstrom, 1991; Binmore and Dasgupta, 1990; Roth, 1979).

The latter, as will be seen, is the "conflict point" in the model proposed here. In fact, it will be seen that such a model is fully consistent with the approach outlined above as point (ii).

Each of these approaches has its strengths and weaknesses. Specifying an extensive form enables us to model the strategic use of private information and, therefore, has implications that could be proved useful for individual bargainers. However, an extensive form is bound to be arbitrary to some extent and the axiomatic approach cuts through disputes about choice of extensive forms (Roth, 1979).

On the other hand there are models of bargaining which assume incomplete information. These models are concerned with situations where each party has private information (e.g. about preferences) that is unavailable to the other parties. This relaxation of the assumptions made in the complete information framework has crucial implications. The most interesting one for economists is the persistence of Pareto-inefficient outcomes in equilibrium, the most striking of which is the existence of disagreement even when mutually beneficial agreements exist. As before in the case of complete information models, the theoretical studies with incomplete information have employed two somewhat different research strategies. The axiomatic approach was pioneered by Harsanyi and Selten (1972). The strategic approach is based on Harsanyi (1967, 1968), whose work supplied the extension of the Nash-equilibrium concept essential to explain games of incomplete information.

In this paper it is first assumed that before strategies are chosen in a formal game played cooperatively, players have complete information, i.e. they may communicate costlessly and without restrictions, and they may choose to enter into any agreement. The non-cooperative solution has the property that in equilibrium no party has an incentive to deviate unilaterally from it (Basar and Olsder, 1982; Mehlmann, 1988; Kaitala et al., 1992). Here two types of equilibria are considered. One is the "social welfare" agreement that seeks to achieve maximum aggregate net benefits. The benchmark against which to judge the benefits of cooperation is, of course, the status quo, which we take to be the "naive" non-cooperative Nash equilibrium. Net benefits in the former case of equilibrium may be distributed unevenly and even be negative for some countries (Mäler, 1989, 1990; Halkos, 1994). In this case, we identify the need for "side-payments" to induce agreement: clearly such side-payments need not be financial, but could be in the form of compensating net benefits from agreement on other issues.

Papers by Hoel (1991), Shogren and Crocker (1991), Mäler (1989, 1990), Harrison and Rutstrom (1991), Kaitala et a1. (1992) and Tahvonen et al. (1993) explore the economics of cooperative and non-cooperative solutions in pollution control problems. Mäler provides a clear analysis of the "acid rain game" and some estimates of the gains from cooperation for European countries; Kaitala et al. (1992) and Tahvonen et al. (1993) model a dynamic game between Finland and four regions of the former USSR. Hoel considers a global pollution problem where all players are affected by the same amount of pollution. Relying on standard economic theory he reinterprets the classic welfare economic theory into a game theoretical framework's without any empirical implementation. In general, it can be said that all these studies provide general forms of cooperative and non-cooperative equilibria but none of them gives any example of an explicit solution.

The idea presented in this paper is that, instead of seeking the cooperative equilibrium values of abatement and then re-distributing the resulting total abatement cost across countries according to some more "equitable" criteria, one could directly seek the Nash and cooperative equilibria. This would incorporate at least some of the "equitability" requirements since the equilibria are obtained from maximization of the countries' coalition's total benefit from pollution control. Moreover, the difference between the Nash equilibria and the cooperative ones could be used as the basis for evaluating each country's gain (or loss) from the coalition. In this case the "equitability" of the cooperative equilibrium could as well be put into discussion. This is because the benefits from cooperation are stated in "efficiency" terms: a cooperative policy bargain can be made which leaves some countries better off, without any other ones being left worse off, i.e. a Pareto preferred bargain.

This paper considers the implications of relaxing the assumption of complete information. It is organized as follows. Sections 1 and 2 introduce formally a simple model in implicit forms under the assumptions of perfect and imperfect information. Similarly, section 3 presents the formulation of the model in explicit terms. Section 4 provides an empirical application of such a model. Finally, section 5 presents some concluding remarks.

1. A PROPOSAL FOR MODELLING EMISSION CONTROL STRATEGIES

In this section the behaviour of countries adopting emission-control strategies is investigated in the following simple model. Let us suppose that N countries, labelled i= 1,2,...,N produce a single good, electricity, denoted Y_i, through the use of fossil fuels. Along with electricity, a "bad" output, sulphur emissions, denoted E_i, is also produced, through the combustion of fossil fuels. The N countries are assumed to be a subset of the total number of countries in the world and the amount of emissions caused by each country is a function of the electricity they plan to produce, i.e.:

$$E_i=E_i(Y_i) \qquad i = 1, 2, \ldots , N \qquad (1)$$

The transboundary nature of the acid rain problem is represented by the following expression

$$D_i = B_i + d_{ii}(1- \alpha_i)E_i + \Sigma_{i\neq j}\, d_{ij}(1- \alpha_j)E_j \qquad (2)$$

where E_i and E_j are the total sulphur emissions per unit of time in country i and j respectively; D_i is the total sulphur deposition per unit of time in country i; α_i is the abatement coefficient in country i; d_{ij} are sulphur depositions in country i per unit of sulphur emissions in country j, i.e. the transfer coefficient from country j to i. Similarly, d_{ii} are sulphur depositions in country i per unit of sulphur emissions in country i. The proportions of emissions from any source country that are ultimately deposited (in the form of acid rain) in any receiving country are presented in the European Monitoring and Evaluation Program of the Norwegian Meteorological Institute (see EMEP, 1993)(1). B_i is the level of background deposition attributable to natural sources (such as volcanoes, forest fires, biological decay, etc) in receptor-country i, or to pollution remaining too long in the atmosphere to be tracked by the model, i.e. is probably attributable not only to natural sources but also to emissions whose origin cannot be determined (2). Then equation (2) reduces to

$$D_i = B_i + \Sigma_j\, d_{ij}\,(1- \alpha_j)E_j \qquad (3)$$

Sulphur deposits cause physical damage which can be measured and expressed in monetary terms, using the damage function

$$Q_i = Q_i(D_i) \qquad i= 1,2, \ldots ,N \qquad (4)$$

which is assumed to be strictly convex in D_i, i.e. $Q_i'(D_i) >0$ and $Q_i''(D_i) >0$. For the damage functions, the existing literature assumes that damage is a linear function of depositions (see Mäler, 1989, 1990; Newbery, 1990). The evidence of sensitivity maps, however, strongly indicates that this is not valid, and that the damage function should be convex: doubling the rate of deposition will more than double the damage caused. Halkos (1992) and Halkos and Hutton (1993) have shown that assuming a linear damage cost function gives the Nash as a dominant market equilibrium. It is also notable that if the true damage cost function is convex instead of linear, which seems probable (and it is assumed in this paper later on) then this will yield an overestimate of the gains from cooperation, as the marginal benefits from reductions in sulphur deposits will be overstated. Also, quadratic damage functions yield interdependence of policies (Halkos and Hutton, 1994). Here, we will assume a quadratic damage function and we will infer its parameters by assuming that countries currently equate national marginal damage cost with national marginal abatement cost.

Given the above, let us suppose that countries face three types of costs:

- first, production costs, denoted PC_i, which will be considered as a datum in the model;
- second, costs of abatement, denoted $CA_i(E_i,\alpha)$, where α_i is, as mentioned, country i's abatement coefficient; and
- third, damage costs, denoted, as in expression (4) above, $Q_i=Q_i(D_i)$.

In discussing costs of abatement, we need to distinguish between primary and secondary abatement. Primary abatement can be done by fuel switching to low- or sulphur-free fuels, by reducing the use of sulphurous fuels as a result of improved fuel efficiency in power plants, and in general by any other measure reducing the output of electricity. Secondary abatement cost functions measure the cost of eliminating tonnes of emissions before (e.g. coal washing), during (e.g. by Fluidized Bed Combustion), or after (e.g. Flue Gas Desulphurization) burning the fuel(3). These vary between countries depending on specific characteristics like fuels used, sulphur content of these fuels, existing or new power plants and on the local costs of implementing best practice abatement techniques. Full details on the secondary abatement cost functions used here are reported in Halkos (1992, 1993, 1994).

In the model proposed in the next section, we assume quadratic (convex) abatement costs, as do Kaitala et al. (1992) and Mäler (1989, 1990). Our purpose is to rely on the level of existing secondary abatement in each European country (if any) and in this way, to assess the optimal contribution of secondary abatement in reaching the environmental targets imposed by current agreements ("30% Club", "New Sulphur Protocol") and to expose the role of primary abatement(4). Let us now consider, in turn, the non-cooperative and cooperative equilibria under the assumptions of perfect and imperfect information respectively.

2. IMPLICIT FORMULATION OF THE MODEL

2.1 Assuming complete information

The Nash equilibrium concept is based on the assumption that countries do not negotiate or communicate in any other way regarding their environmental policies; each country acts in a non-cooperative way taking the environmental policy of other countries as given. It is assumed that countries are rational and behave like Cournot (Nash) duopolists, in a non-cooperative game theoretic framework. Then the net benefit from electricity production of each country, denoted $NB_i(Y_i,\alpha_i)$ will be defined as the difference between the value of production, $p_i\, Y_i$, where $p_i=p_i(Y_i)$ is the market price of electricity in country i, and the above mentioned three types of costs, i.e.:

$$NB_i(Y_i,\, \alpha_i) = p_i\,(Y_i)Y_i - PC_i - CA_i(E_i,\alpha_i) - Q_i(D_i) \qquad (5)$$

Considering this simple model from a game theoretic point of view, it can immediately be seen that the Nash equilibrium is ensured by those values (α_i^*, Y_i^*) which solve the following problem:

$$\text{maximize } NB_i = p_i\, Y_i - PC_i - CA_i(Y_i,\alpha_i) - Q_i(Y_i,\, \Sigma_j Y_j,\, \alpha_i,\, \Sigma_j \alpha_j) \qquad (6)$$

$$\text{subject to} \qquad p_i = p_i\,(Y_i)$$

for country i. Another theoretical possible non-cooperative equilibrium is the Von Stackelberg solution according to which one country is assumed to have superior information (for more details see Halkos, 1992; Halkos and Hutton, I994).

However, the transboundary nature of the acid rain problem makes it obvious that some kind of cooperation between countries could be needed. More specifically, one must consider the terms of bargaining between countries embodied in the model, where the term bargaining means the negotiations between countries about the terms of possible cooperation in pollution control. One possible way of defining a cooperative equilibrium abatement strategy could be the following:

$$\underset{\alpha_i,\ Y_i}{\text{Maximize}}\ \Sigma_i\, NB_i$$

$$\text{subject to} \qquad 0 \leq \alpha_i \leq 1 \tag{7}$$

The solution concept to this problem implicitly requires transferable utility, i.e. that gains in one country can be transferred to other countries in order to achieve another distribution of gains and losses.

2.2 Assuming imperfect information

Under complete information, all players by assumption know the exact payoffs (benefits) that their opponents can obtain. This is a demanding assumption. To assign the benefits from certain actions it is necessary to know the expected benefits each player obtains. But expected benefits capture individual characteristics such as attitudes towards risk. In this section the analysis will be carried out with the assumptions of incomplete information and risk neutral players.

For our purposes, it can be said that acidic emissions may be deterministic in the sense that countries are able to choose adequate abatement strategies to determine the final level. Conversely, deposits of each country could be considered as a continuous random variable due to the influence of atmospheric and geologic factors that countries cannot really control and some probability limits can be assumed. We could think of a probability density function $f_i(D_i)$ of the actual level of deposits D_i in i=1,2, ... ,N different countries to be defined in an interval $[B_i, B_i+\Pi_i)$ such that

$$\int_{B_i}^{B_i+\Pi_i} f_i(D_i)d(D_i) = 1 \tag{8}$$

where B_i denotes background deposits explained above and Π_i for $i \neq j$ is defined as:

$$\Pi_i = \sum_{j=1}^{N-1} d_{ij}E_j + d_{ii}E_i \tag{9}$$

Therefore, the possibility for countries to set adequate abatement efficiency influences only the range in which the final value of the (continuous and strictly positive) random variable D_i is more likely to occur. A greater probability of occurrence for values nearer $B_i+\Pi_i$ is due to the fact that high levels of deposits certainly cause a negative externality to the country, but abatement cost increases more than proportionately with the amount of pollutant removed so that lower levels of (α_i, $\Sigma_j\alpha_j$), would determine energy cost savings for the countries, although at the "price" of higher deposits. It is worth mentioning that it is not only weather that determines the range of D_i for a given pattern of emissions. As we have seen, the energy cost savings made possible by higher deposits, i.e. lower abatement levels, cause an asymmetric behaviour of the probability distribution of deposits and therefore a greater occurrence of values of D_i nearer to $B_i + \Pi_{i.}$

Therefore, both equation (9) and the argument that deposits are depletable (i.e. what is not deposited in one country must be necessarily distributed among the others, or some others), allow us to consider deposits in different countries as dependent random variables, whose joint probability density function is defined as follows:

$$g(D_i, D_j) = f_i(D_i) f_j(D_j / D_i) \tag{10}$$

Of course, $g(D_i, D_j)$ would be such that:

$$\int_{B_j}^{B_j+\Pi_j} g(D_i, D_j) d(D_j) = f_i(D_i) \tag{11}$$

according to the statistical definition of marginal distribution.

Recalling that emissions do not only cause damages of various kinds but also produce "benefits" such as the mentioned energy cost savings (made possible, for instance, by the use of high rather than low sulphur content fuels, so that resources otherwise allocated to abatement with the emission reductions, country's i expected benefit from pollution control can be introduced as follows:

$$EB_i = \sum_{j=1}^{N} c_j \int_{B_j}^{B_j+\Pi_j} \int_{D_i=D_j}^{B_i+\Pi_i} g(D_i, D_j) D_i dD_i dD_j - CA_i(D_i) \tag{12}$$

where c_j is the marginal abatement cost per unit of pollutant removed and $CA_i(D_i)$ is the abatement cost. Expression (12) represents, for each of the i= 1, 2, ..., N countries, the so-called "payoff function": the double-integral's setting and limits appear then more clear, in so far as they show that countries quantify their uncertainties -in this case, concerning deposits - using subjective probability distributions and taking the other countries' behaviour as given (see the second integral's lower limit $D_i=D_j$ in expression (12). Similarly, expression (10) defines for each of the i=1,2,...,N countries the so-called "beliefs", represented in game theory by subjective probability distributions over a set of possible "states of the world" -described, in our case, by the occurrence of different deposition levels.

In turn, the introduction of an explicit deposits target D_i to be met by the country under consideration (for instance, a single country might want to pursue its own deposition target independently of any joint action with other countries) would modify expression (12) as follows:

$$EB_i = \sum_{j=1}^{N} c_j \int_{B_j}^{B_j+\Pi_j} \left[\int_{D_i=D_j}^{B_i+\Pi_i} g(D_i, D_j) D_i dD_i dD_j - \int_{B_i+\Pi_i}^{\bar{D}_i} g(D_i, D_j) D_i dD_i dD_j - CA_i(D_i) \right] \tag{13}$$

where the term $-\int_{B_j}^{B_i+\Pi_i} \int_{B_i+\Pi_i}^{\bar{D}_i} g(D_i, D_j) D_i dD_i dD_j$ represents the cost for country i of reducing deposits from D_i to some target level $\bar{D}_i$. Let us now consider the model explicitly.

3. EXPLICIT FORMULATION OF THE MODEL

3.1 Assuming complete information

Some specific functional forms for total damage and abatement costs can now be assumed, for the purpose of giving an example of "efficient" emission control policy, which will show how each country's abatement strategy is able to influence the strategies of other countries in a non-cooperative game theoretic framework such as the one sketched so far. For instance, assuming quadratic total damage and abatement costs in deposits and emissions respectively, i.e. $TC_{damage,i}=\gamma_i D_i^2$, where D_i is given by expression (3) and $TC_{abatement,i}=\beta_i(\alpha_i E_i)^2$, where α_i indicates country i's abatement coefficient, E_i its unconstrained emissions and γ_i and β_i are parameters explained later on (in section 4), then the total cost that country i will seek to minimize is

$$C_i=TC_{production,\,i}+TC_{abatement,\,i}+TC_{damage,\,i}=TC_{production,\,i}+\beta_i(\alpha_i E_i)^2+\gamma_i D_i^2 \qquad (14)$$

The first order conditions (FOCs) $\partial C_i/\partial\alpha_i=0$ will give us the reaction function of each country i and the solution of these N FOCs will give us the Nash non-cooperative equilibrium values. It is implicitly assumed that the abatement values lie between 0 and 1 (i.e. $0\leq\alpha_i\leq1$) because they are obtained from an "unconstrained" minimization problem (simply ($\partial C_i/\partial\alpha_i=0$).

Similarly, the cooperative set-up of the model can be written as follows:

$$\begin{aligned}&\underset{\alpha_i}{\text{Minimize}} && \Sigma_i C_i\\ &\text{subject to} && 0\leq\alpha_i\leq1\end{aligned} \qquad (15)$$

The combination of abatement which minimizes the total abatement costs and social environmental damage costs across countries will be referred to, in this case, as the social welfare cooperative solution. The first order conditions of problem (15) are $\partial(\Sigma_i C_i)/\partial\alpha_i=0$

and these conditions will give us first the reaction line of each country i, and then the unique cooperative or "social-welfare" equilibrium values.

3.2 Assuming incomplete information

Let us consider D_i as a continuous random variable and let us assume a certain probability value comprised between "reasonable" limits, that is, within a finite support which will be formed by an "upper bound" deposition level, called D_{Ui}, and a lower bound level, called D_{Li}. Such bounds will be defined as:

$$D_{Li} = d_{ii}(1-\alpha_i)\mathrm{E}_i + \mathrm{B}_i \qquad \alpha_j=1 \qquad (16)$$

$$D_{Ui} = d_{ii}(1-\alpha_i)\mathrm{E}_i + \Sigma_j d_{ij}\mathrm{E}_j + \mathrm{B}_i \qquad \alpha_j=0 \qquad (17)$$

In other words, (16) assumes that countries are actually practising the maximum abatement, as it can be obtained by setting $\alpha_j=1$ in expression (3); whereas (17) assumes that countries are not abating anything, so that country i receives the entire proportion of all other countries' emissions $\Sigma_j d_{ij}E_j$ as proved by setting $\alpha_j=0$ in (3).

Then, in order to keep the analysis simple it will be assumed that deposits are equally likely to assume values between the lower and upper bounds defined so far; i.e. we assume that deposits are determined on the basis of a uniform probability function, which will be defined as follows:

$$f_i(D_i) = \frac{1}{D_{Ui} - D_{Li}} \qquad i=1, 2,\ldots, N \qquad (18)$$

Having then introduced this "new" definition of deposits, we can examine, again in the case of country i for our expository purposes, what the total costs for that country become. In fact, using (18), the minimization of the sum of production, abatement and random damage costs for country i will be:

Minimize $$TC_i = TC_{production} + \beta_i \alpha_i^2 E_i^2 + \gamma_i \int_{D_{Li}}^{D_{Ui}} \frac{1}{D_{Ui} - D_{Li}} D_i^2 \, dD_i \qquad (19)$$

That is the difference between (19) and, for instance, (14) in the case of certainty, is represented by the random term in damage costs, given by expression (18), which clearly models country i's "expectations" concerning the value of its own deposits, and therefore of its own damage cost. Notice that in this way (i.e. by allowing for random deposits) the somewhat restrictive assumption of country i having complete information about countries j' s abatement coefficient values α_j -necessary for deriving the Nash equilibrium set-up of the model under certainty- is avoided here.

In this more reasonable case, country i does not have perfect information concerning countries j's abatement strategies but, as we will see, a Nash equilibrium will still be possible, since country i, by expression (18) is able to compute a subjective probability over the other countries' behaviour and therefore over its own costs which must be minimized. Returning to expression (19) and omitting, for reasons of simplicity, the cost of production, we obtain:

Minimize $$TC_i = \beta_i \alpha_i^2 E_i^2 + \frac{\gamma_i}{3} \frac{(D_{Ui}^3 - D_{Li}^3)}{D_{Ui} - D_{Li}} = \beta_i \alpha_i^2 E_i^2 + \frac{\gamma_i}{3} (D_{Ui}^2 + D_{Ui} D_{Li} + D_{Li}^2) \qquad (20)$$

so that, as already mentioned, the Nash equilibrium abatement rates can be found by solving the FOCs, $\partial TC_i / \partial \alpha_i = 0$, which will give us first the reaction functions of each country i and then the Nash solutions.

Comparing the FOCs of problems (20) and (14) it can be said that country i's abatement coefficient under the assumption of "stochastic" deposits will be smaller than the abatement coefficient that country i would select under the assumption of "deterministic" deposits only if

$$\Sigma_j d_{ij} E_j (\alpha_j - 0.5) > 0 \qquad (21)$$

We can then conclude this part of the discussion by saying that market equilibrium may well be reached under uncertainty concerning deposits - and therefore damage costs -but that such equilibrium presents some "inefficiency" with respect to the certainty Nash equilibrium, since it leads to abatement choices that might overestimate - or underestimate -the real damage they will cause. However, the question whether something "better" could be attained by some kind of joint action or cooperation with other countries is quite significant in the analysis of the economics of acidification in Europe.

Let us now consider the cooperative set-up in the case of incomplete information. Recalling (20) we have:

$$\text{Minimize} \qquad SW = \Sigma_i [\beta_i \alpha_i^2 E_i^2 + \frac{\gamma_i}{3}(D_{Ui}^2 + D_{Ui} D_{Li} + D_{Li}^2)] \qquad (22)$$

and solving the FOCs (i.e. $\partial SW / \partial \alpha_i = 0$) we can derive the abatement coefficients under uncertainty for each country i. Then, comparing the FOCs of problems (22) and (15), it can be said that if

$$\beta_i + \gamma_i d_{ii}^2 + \Sigma_j \gamma_j d_{ii}^2 < 1 + \gamma_i d_{ii}^2 + \frac{\Sigma_j \gamma_j d_{ii}^2}{3}$$

or

$$\beta_i + \frac{2\Sigma_j \gamma_j d_{ii}^2}{3} < 1$$

then country i's abatement coefficient under uncertainty will be smaller than the abatement coefficient that country i will choose under certainty. This makes sense because countries under certainty are prepared to abate more than under uncertainty.

Finally, cooperative and non-cooperative solutions of the game embodied in the proposed model could be compared to assess the benefits of cooperation. The empirical evidence on the magnitude of these potential cooperation gains suggests that they might be quite significant (Mäler 1989, 1990; Halkos, 1994). In this respect, the social welfare maximizing case becomes fully relevant. The model presented in this section could then be regarded as a useful "tool" to describe and interpret such a reality: for this reason, in the next section a simulation of the model is provided.

4. AN EMPIRICAL APPLICATION OF THE MODEL

4.1 Simulation

Preliminary steps need to be considered, which relate to the fact that it is the monetary values of abatement and damage costs that must be considered in the empirical test of the model. More precisely, the total-cost formula was:

$$TC_i = TC_{abatement,\, i} + TC_{damage.\, i} = \beta_i\, \alpha_i^2 E_i^2 + \gamma_i\, D_i^2$$

where TC_i the total cost of country i (i=1,2,...,N). The method used to estimate the monetary coefficient β_i is the following. First, the relationship

$$TC_{abatement,\, ik} = a + b_i\, TSR_{ik}^2 + u_{ik}$$

for country i and for the value k of TSR (= $\alpha_i E_i$), is estimated by ordinary least squares (OLS); and where a is a constant, u is a disturbance term and TSR is the total amount of sulphur removed(5).

We calibrate the damage function by assuming that national authorities act as Nash partners in a non-cooperative game with the rest of the world, taking deposits originating in the rest of the world as given. To obtain the damage cost's monetary value γ_i we have:

$$TC_i = [a + b_i\, (\alpha_i^2\, E_i^2)] + \gamma_i\, [d_{ij}\, (1 - \alpha_i) E_i + \Sigma_{i \neq j}\, d_{ij}\, (1 - \alpha_j) E_j]^2$$

Then, letting the first derivative of the above with respect to α_i be equal to zero gives:

$$\frac{\partial TC_i}{\partial \alpha_i} = 0 \Rightarrow 2 b_i \alpha_i E_i^2 - 2 \gamma_i D_i (d_{ii} E_i) = 0$$

i.e. $$\gamma_i = \frac{b_i (\alpha_i E_i)}{d_{ii} D_i}$$

In order to model the political unification of Germany, the damage coefficient of the FRG has been used for both countries (FRG and GDR) for the year 2000. The trade-off of sulphur on which the results of the paper are based is drawn from the EMEP model. This is based on the old European boundaries. However, it turns out that it is useful to work with "old data". It does not make much sense to aggregate FGR and GDR simply for the sake of using current boundaries because historic policies in the two areas have been so different. Also, as our calibration is based on the year 1990 it is necessary to treat the former USSR and Czechoslovakia as political units even in the year 2000.

Finally, the unconstrained sulphur emissions used here are based on research conducted by IIASA for the years 1990 and 2000. The emissions for the year 1990 are net (i.e. after secondary abatement) while these for the year 2000 are gross (Amann and Sorensen, 1991). For 1990 and for calibration of the damage function, we have estimated gross emissions using the existing secondary abatement level of European countries in 1990.

4.2 Empirical results

In this section the results obtained by the model are interpreted. Tables 1-3 present the abatement rates (%) and the total abatement and damage costs under certainty and uncertainty for the year 2000 and in the cases of non-cooperation (Nash) and cooperation (Social Welfare maximization). Looking at table 1 it can be seen that the Nash abatement rates are considerably higher under uncertainty than under certainty for the USSR and FRG (more than twice as much), and GDR; and somewhat higher for Bulgaria, Czechoslovakia, Italy, Poland, Romania, Spain, Turkey, the UK and Yugoslavia.

Similarly, the social welfare solution is much higher under uncertainty than under certainty for GDR and FRG, and somewhat higher for Turkey and USSR. The optimal cooperative solution finds countries like Austria, Belgium, Bulgaria, Czechoslovakia, Greece, Ireland, Luxembourg, Poland, Spain, USSR and the UK having to abate much more than the amount of their Nash non-cooperative solution. On average, the Nash non-cooperative solution under certainty is 4.5% while the social welfare solution is approximately 10%. These averages are low because they rely on the existing secondary abatement in Europe in 1990. Although there are countries like Austria, Denmark, Finland, FRG, the Netherlands and Sweden where secondary abatement takes place, in most of the other European countries secondary abatement does not exist or it is very low.

From Tables 2 and 3 it can be seen that the Nash abatement costs are similar under certainty and uncertainty for most European countries, except for the FRG (more than twice as much), GDR and USSR but the Nash total damage costs are quite different (a result expected according to the assumption of imperfect information regarding deposits). Under uncertainty the main polluters (Eastern European countries, FRG, Italy, Spain, Turkey and the UK) abate more. Countries receiving large amounts of sulphur deposits from others abate less: Austria, Denmark, Luxembourg, Netherlands and the Scandinavian countries. The total damage costs are higher under uncertainty only for the FRG, Poland, Spain, USSR, and the UK. For the rest of the European countries the Nash damage cost is much lower under uncertainty.

In terms of totals, the Nash abatement costs are \$884 m and \$1037 m under certainty and uncertainty respectively. As mentioned the increase in Nash abatement costs is carried mainly by FRG, GDR and USSR. The Nash damage costs are \$1229 m and \$901 m under certainty and uncertainty respectively. If countries cooperate then total abatement cost is \$1006 m and \$1078 m under certainty and uncertainty respectively. The abatement costs under uncertainty are higher only for the FRG and Turkey. Besides, in terms of cooperative damage costs we have \$1063\$ m and \$851 m under certainty and uncertainty respectively.

Finally, table 4 summarizes the results obtained by each strategy under certainty and uncertainty for the year 2000. It can be seen that, if countries cooperate under certainty they will have to pay an extra 14% of the total Nash abatement cost. This will result in an extra 1.71 million tonnes of sulphur reduction and approximately 14% less damage cost. Similarly if countries cooperate under uncertainty they will have to pay an extra 4% of the Nash total abatement cost and this will reduce sulphur emissions by 621 million tonnes which is only one third of the level achieved under certainty. Comparing the totals under certainty and uncertainty it can be seen that the Nash abatement costs are 17% higher under uncertainty and Nash damage costs 27% higher under certainty.

It is notable that although for most countries the Nash abatement costs are similar under certainty and uncertainty, Germany (FRG and GDR) and USSR make the difference. If countries cooperate then abatement costs are 7% higher and damage cost 20% lower under uncertainty. But cooperation results in much higher abatement levels under certainty (1.7 m tonnes) than under uncertainty (621 m t). Also the gains from cooperation are much higher under certainty (45 m $) than under uncertainty (approximately 9 m $). Obviously, under the assumption of stochastic deposits the gains from cooperation are much less than under the assumption of deterministic deposits.

TABLE 1: Abatement rates under certainty and uncertainty (%)

Countries	Nash Certainty	Nash Uncertainty	Social Welfare Certainty	Social Welfare Uncertainty
Albania	0.99	0.56	1.9	0.85
Austria	5.5	2.5	17.0	10.2
Belgium	0.9	0.8	20.0	1 1.5
Bulgaria	1.2	1.3	9.2	5.0
Czechoslovakia	2.9	3.8	9.5	7.4
Denmark	7.9	2.72	11.0	4.3
Finland	2.6	1.03	3.0	1.14
France	5.3	4.9	11.0	8.11
GDR	25.2	36.3	30.2	40.5
FRG	23.0	47.4	26.0	48.4
Greece	0.94	0.8	11.0	0.88
Hungary	0.9	0.9	2.2	1.6
Ireland	0.84	0.6	4.8	2.4
Italy	0.92	1.4	3.2	2.2
Luxembourg	5.82	1.5	29.0	20.7
Nether.	12.7	3.9	23.0	12.3
Norway	2.54	0.31	4.5	0.92
Poland	0.8	1.3	3.5	2.6
Portugal	0.85	0.7	1.3	0.9
Romania	0.84	1.1	1.5	1.43
Spain	0.92	1.5	6.0	3.4
Sweden	3.7	1.6	7.0	2.4
Switzerland	6.2	1.41	9.0	3.4
Turkey	1.6	2.04	I.7	2. I
USSR	4.2	10.3	13.7	I3.9
UK	0.99	1.7	4. I	2.95
Yugoslavia	0.84	1.1	3.0	2.03
Average	4.48	4.943	9.9	7.9I

TABLE 2: Total abatement costs under certainty and uncertainty for the year 2000 (in 1985 $US m)

Countries	Nash Certainty	Nash Uncertainty	Socia1 Welfare Certainty	Socia1 Welfare Uncertainty
Albania	0.0033	0.00102	0.0095	0.0023
Austria	0.173	0.33	2.035	0.525
Belgium	0.014	0.0098	10.3	2.23
Bulgaria	0.9266	0.93	1.3	1.011
Czechoslovakia	48.37	48.82	56.3	51.91
Denmark	0.73	0.074	1.5	0.185
Finland	16.17	16.065	16.2	16.07
France	38.79	38.321	47.3	41.38
GDR	134.43	143.0	168.9	158.06
FRG	101.64	245.33	135.2	255.49
Greece	17.65	17.645	17.67	17.65
Hungary	16.35	16.351	16.61	16.45
Ireland	0.0053	0.0027	0.184	0.042
Italy	100.5	100.66	101.93	101.063
Luxembourg	0.0144	0.001	0.65	0.1624
Netherlands	5.22	3.51	11.42	4.702
Norway	0.027	0.0004	0.088	0.0033
Poland	81. 15	81.3	82.91	82.01
Portugal	8.85	8.85	8.871	8.852
Romania	38.05	38.1	38.19	38.17
Spain	90.02	90.1	91.81	90.57
Sweden	0.118	0.02	0.4	0.046
Switzerland	0.434	0.02	1.0	0.1151
Turkey	38.32	38.46	38.34	38.471
USSR	0.43	2.38	5.66	4.323
UK	93.15	93.62	97.71	95.182
Yugoslavia	52.81	52.83	53.2	52.961
Total	884.35	1036.73	1005.69	1077.64

TABLE 3: Total damage costs under certainty and uncertainty for the year 2000 (in 1985 $US m)

Countries	Nash Certainty	Nash Uncertainty	Social Welfare Certainty	Social Welfare Uncertainty
Albania	0.904	0.1251	0.87	0.122
Austria	11.773	0.9743	10.12	0.741
Belgium	3.198	0.9779	2.35	0.703
Bulgaria	0.765	0.3773	0.67	0.341
Czechoslovakia	41.5	29.53	36.13	27.077
Denmark	38.3	1.775	34.6	1.567
Finland	19.12	1.263	16.99	1.169
France	118.38	40.251	105.81	37.03
GDR	203.4	101.311	162.84	85.85
FRG	504.02	565.825	433.13	544.28
Greece	8.05	2.568	7.69	2.522
Hungary	10.98	4.971	10.37	4.83
Ireland	1.302	0.2934	1.22	0.274
Italy	20.06	19.51	18.96	19.083
Luxembourg	0.97	0.0365	0.713	0.0182
Netherlands	64.79	2.121	53.3	1.368
Norway	12.05	0.082	11.09	0.068
Poland	20.19	22.03	18.29	21.25
Portugal	3.05	0.919	2.94	0.903
Romania	11.87	8.863	11.33	8.722
Spain	5.83	6.329	5.32	6.032
Sweden	16.51	I. 184	15.03	1.094
Switzerland	39.83	0.842	36.48	0.711
Turkey	20.68	13.964	20.17	13.88
USSR	13.84	33.359	11.48	31.64
UK	30.23	36.035	28.231	34.84
Yugoslavia	7.34	5.361	6.92	5.22
Total	1228.93	900.88	1063.04	851.14

TABLE 4: Abatement and damage costs (in US $m) and sulphur removed (in 1000 t)

Strategy	Certainty	Uncertainty
Nash abatement cost	884.35	1036.73
Nash damage cost	1228.93	900.88
Total Nash abatement cost	2113.28	1937.61
Nash sulphur removed (level)	1438	2176
Nash sulphur removed (%)	4.5%	5%
Social welfare abatement cost	1005.69	1077.64
Social welfare damage cost	1063.04	851.14
Total social welfare abatement cost	2068.73	1928.78
Social welfare sulphur removed (leve1)	3146	2797
Social welfare sulphur removed (%)	10%	8%
Difference from Nash		
Abatement cost	-121.34	-40.91
Damage cost	+ 165.89	+49.74
Net	+44.55	+8.83
Sulphur removed	+ 1708	+621

5. **Summary and conclusions**

In this paper, different equilibria concepts have been considered under the assumptions of stochastic and deterministic sulphur deposits. One of the different equilibria was the Nash, where each country minimizes only its own pollution control costs. But in global environmental problems each country's own contribution to worldwide emissions is relatively small so that there is little a country can do by itself. This interdependence across countries provides a case for cooperation in sulphur emissions control policies (particularly in Europe), since by cooperation of national policies a given set of deposition goals can be attained at a lower cost than if each country acts in isolation. Distinguishing between certainty and uncertainty about deposits, it was shown that:

1. Relying on the existing (if any) secondary abatement in Europe, it can be said that, in order to achieve the environmental targets set by International Agreements (for instance, "30% Club", "New Sulphur Protocol") it is required that countries will have to use primary abatement. Targets less the optimal cooperative secondary abatement provide an estimate of the required primary contribution, which seems to be quite

high(6). Otherwise, targets will not be satisfied (for more details see Halkos and Hutton, 1994).

2. Under uncertainty the gains from cooperation are much less than under certainty.
3. Germany dominates the effort as its initial abatement is high. The old FRG has to abate more than twice as much under uncertainty and it is the only country (except for USSR) for which damage costs are higher under uncertainty. Additionally, although the Nash abatement costs are similar under certainty and uncertainty Germany is again an exceptional case.
4. The Nash abatement costs are similar under certainty and uncertainty for most countries (except for GDR, FRG and USSR).
5. The Nash damage costs are quite different due to the assumption of stochastic deposits. Under uncertainty countries will face much less damage costs (except for FRG, Poland, Spain, USSR, UK).
6. Main polluters abate more under uncertainty while pollutees abate more under certainty.

Finally, it is obvious that the nature of uncertainty matters. Here, a uniform probability function was assumed for the deposits. This work can be extended by considering different forms of probability density functions and their implications for the analysis. Also, an obvious area for further research is how the change in European boundaries affects the results. It would, however, be equally interesting to disaggregate the data to the levels of grids (squares) in order to evaluate the consequences of local differences in either emissions or sensitivity to depositions.

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NOTES

(1) The estimates of the tonnes of sulphur emissions and the subsequent deposits between countries are based on the EMEP (1993) model (European Monitoring and Evaluation Program, Norwegian Meteorological Institute). The proportional transfer coefficients of the EMEP's transfer matrices have been used with IIASA's unconstrained sulphur emission estimates for the year 2000 (Amann and Sorensen, 1991) To derive a transfer matrix of a closed system of 27 countries.

(2) The background deposits have been excluded as it is impossible to be tracked by our model.

(3) Other types of abatement options that are omitted in this approach are abatement through energy conservation in its broadest sense (energy demand suppression, fuel switching, and efficiency measures) and fuel substitution.

(4) For more details on the existing secondary abatement in Europe at 1990 and the future plans for installation of abatement technologies, see Halkos (1992) and Halkos and Hutton (1994). For the "New Sulphur Protocol" see Klaasen (1993) and IIASA (1993).

(5) Originally, the model was estimated as $TC_{abatement,i} = a+d_iTSR_i+b_i\,TSR_i^2$. d_i was constrained to zero, however, for avoiding negative abatement solutions. Also, in the explicit set-up of the model and for reasons of simplicity we preferred τo use β_i rather than all the monetary coefficients a, d_i and b_i. Obviously, after constraining d_i=0, $\beta_i=\{[a/(\alpha_i^2E_i^2)]+b_i\}$.

(6) Sulphur emissions can be reduced through either conservation or energy improvements. The latter can be achieved for instance by reducing energy consumption through more efficient generation, use of combined heat and power, etc. Low sulphur coal may be a good way to reduce emissions where emission standards are met by using coal within a specific range of sulphur content. For instance, a standard of 2000 mg/m^3 is equivalent to approximately 1% sulphur content of coal, as the cut-off level above which sulphur abatement technologies would be used. Emission standards between 1000 and 2000 mg/m^3 are equivalent τo coal sulphur content of 0.5-1% and there is no percentage removal requirement. Plants facing these standards can use either low sulphur content coal alone, or in conjunction with a limited-efficiency abatement technique (Vernon, 1989). Substitution of fossil fuels by nuclear power and natural gas is also possible. Public pressure may increase the demand for gas fired power plants. High capital cost and costs of decommissioning mean that the nuclear plants have no advantage over coal-fired plants with secondary emissions control.

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