International negotiations on acid rains in Northern Europe: a discrete time iterative process

by M. Germain[1], Ph.L. Toint[2] and H. Tulkens[3]

Report 95/7 September 15, 1995

[1] CORE, Université Catholique de Louvain.
Email : germain@core.ucl.ac.be

[2] Department of Mathematics, Facultés Universitaires ND de la Paix,
61, rue de Bruxelles, B-5000 Namur, Belgium, EU
Email : pht@math.fundp.ac.be
Current reports available by anonymous ftp from the directory
"pub/reports" on thales.math.fundp.ac.be (internet 138.48.4.14)

[3] CORE and IRES (Institut de Recherches Economiques et Sociales),
Université Catholique de Louvain,
and Facultés Universitaires Saint-Louis, Bruxelles.

International negotiations on acid rains in Northern Europe: a discrete time iterative process*

Marc Germain † Philippe L. Toint ‡ Henri Tulkens §

September 15, 1995

Abstract

This paper proposes a dynamic model of international negotiations on transboundary pollution. The approach is characterized by a discrete time formulation (at variance with the continuous model of Kaitala *et al.* (1995)) and by a suitable reformulation of the local information assumption on cost and damage functions: at each stage of the negotiation, the parties assign the best possible cooperative state, given the available information, as an objective for the next stage. It is shown that the resulting sequence of states converges to a Pareto optimum in a finite number of stages. Furthermore, a financial transfers' structure is formulated, which guarantees that the desired sequence of states is rational for the involved parties, at the individual as well as at the coalition level. The concepts are applied in a numerical simulation of the SO_2 transboundary pollution problem relating to acid rains in Northern Europe.

1 Introduction

The modeling of international negotiations on transboundary pollution has received a lot of attention in the recent past. Amongst the many contributions in this area, Chander and Tulkens (1991, 1992) present a general dynamic framework for such models, and an application is provided by Kaitala *et al.* (1995) in the context of the "acid rain game" in Northern Europe, that is, the problem of negotiating coordinated reductions of SO_2 emission levels in Finland, Russia and Estonia.

*The first and third authors' work was achieved in the framework of the project "Environmental Policy, International Agreements and International Trade" of the European Union (DG XII), coordinated by Professor Alistair Ulph and CEPR, London. It is also part of convention nr 2.4589.92 between the Center of Operations Research and Econometrics (CORE) and the Fonds de la Recherche Fondamentale Collective (FRFC), Brussels, and was on that basis included in the tasks assigned to the HCM network "Designing Economic Policy for Management of Natural Resources and the Environment" coordinated by Professor Anastasios Xepapadeas. A first version was presented at the Rethymno meeting of the network in september 1994. For the completion of this version, Germain acknowledges the financial support of the Université Catholique de Louvain under its FDS project nr 7-29039.

†CORE, Université Catholique de Louvain.

‡Département de Mathématique, Facultés Universitaires Notre-Dame de la Paix, Namur.

§CORE and IRES (Institut de Recherches Economiques et Sociales), Université Catholique de Louvain, and Facultés Universitaires Saint-Louis, Bruxelles.

The methodology proposed by these authors does not require that the information available to the negotiating parties be *global*, as is the case for instance in Mäler (1989) or Kaitala and Pohjola (1994). It is rather supposed that this information is *local* in that it is limited to the marginal values of emission abatement costs and pollution damage costs to the environment, in a context where time is assumed to be continuous.

Although an improvement on global information models, this proposal has the drawback that it requires, in theory, that the parties continuously negotiate, a quite unrealistic situation. The purpose of the present paper is to reconsider this methodology and to improve the realism in its representation of time while suitably adapting the assumptions made on the local nature of information.

More specifically, we will assume that negotiations are separated into well determined and distinct stages, and that the negotiating parties know, at each stage, their emission abatement and damage cost function only up to certain thresholds determined by exogenous technological constraints. At each stage, the parties then assign as a common objective the best cooperative state they can determine, given the available information. As these thresholds evolve with the progress made in reducing pollution, we show that a finite number of such negotiation stages lead the involved parties to a Pareto optimum. Besides indicating that only a finite number of negotiation stages is necessary to reach the optimum, this new approach has the advantage of clarifying the associated time scale, where negotiations and periods between them are clearly distinguished.

However, each of the negotiating parties will continue to cooperate in such a process only if it finds cooperation individually profitable. Moreover, the stability of the program requires that none of the parties can find an advantage in abandoning it. Chander and Tulkens (1991, 1992) therefore propose, in the context of their continuous model, a financial transfers' scheme ensuring that emission abatement costs are shared amongst all parties in such a way that the gains obtained are increasing with time, and are larger than those resulting from the constitution of coalitions. We shall make use of this transfers' scheme in this present discrete time model, and show that they guarantee that it is in the interest of all parties to cooperate until the end of the pollution reduction program, i.e. until the international optimum is reached.

2 The global problem and its approach in continuous time

The problem is as follows. We consider n regions in which some atmospheric pollutant (such as SO_2) is emitted with certain non-negative emission levels $\{E_i\}_{i=1}^n$. Once emitted this pollutant is then transported by winds across the regions, this interregional transport being described by a $n \times n$ matrix A, whose i,j-th element $a_{ij} \geq 0$ is the fraction of the pollutant emitted in region j and deposited in region i. If we define by B the n-vector of pollutant depositions with natural origin, the vector Q of total pollutant depositions in the n regions satisfies the relation

$$Q = Q(E) = AE + B, \tag{2.1}$$

where A and B are supposed to be constant and exogenous, and where we have denote by E the vector $(E_1, \ldots, E_n)^T$. We assume that (2.1) holds at each moment in time: the fact that B is constant then implies that the pollutant does not accumulate in the regions.

We associate two cost functions with each region. The first, denoted $C_i(E_i)$, expresses the emission abatement costs required by an emission level E_i in region i. We assume that $C_i(\cdot)$ is decreasing for all positive emission levels E_i, which simply means that every emission reduction generates costs for the emitting region. The second, denoted $D_i(Q_i)$, measures the monetary value of the damage to the environment caused by a deposition Q_i in region i. We also assume that $C_i(\cdot)$ and $D_i(\cdot)$ are continuous and convex. As a result, we may thus associate, with each region, an aggregate cost function

$$J_i(E) = C_i(E_i) + D_i(Q_i(E)), \tag{2.2}$$

where the depositions $Q_i(E)$ are given by (2.1).

We are then interested in minimizing the total cost for all regions, that is in achieving the emission levels $\{E_i^*\}_{i=1}^n$ obtained as solution of the program

$$\min_E J(E) = \sum_{i=1}^n J_i(E) \tag{2.3}$$

such that (2.1) holds and

$$E_i \geq 0, \qquad (i = 1, \ldots, n). \tag{2.4}$$

It is crucial to observe that solving the program (2.3)–(2.1)–(2.4) requires that the cost functions $C_i(\cdot)$ and $D_i(\cdot)$ are known for all possible values of their argument. However, this can be unrealistic when the current emission levels and depositions are very different from the optimal ones: such an extensive knowldege of the cost functions may be very hard to obtain, or may be too unreliable to be used in effective interregional negotiations.

Kaitala *et al.* (1995) propose[1] to alleviate this difficulty by only assuming that the regions know their cost functions *locally*, that is at the margin. It is then possible to define an emission reduction program governed by the differential system

$$\frac{dE_i}{dt}(t) = -K\left[C_i'(E_i(t)) + \sum_{j=1}^n a_{ji} D_j'(Q_j(E(t)))\right], \; (i = 1, \ldots, n), \tag{2.5}$$

where we use the notation $E_i(t)$ to indicate that the emissions now depend on time (they are still related to the depositions by (2.1)), and where K is a positive constant. Because the term between square brackets vanishes when the first order optimality conditions of (2.3)–(2.1)–(2.4) hold for strictly positive emission levels, it is possible to prove that these levels converge to their

[1] Following Tulkens (1979), whose model is inspired by the literature on "resource allocation processes" (Arrow and Hurwicz (1977), Malinvaud (1970-71) and Drèze and de la Vallée Poussin (1971)). All these processes are formulated in continuous time. Champsaur, Drèze and Henry (1977) have proposed a discrete time version which was found to be ill-adapted to the international problem considered here. This is why the present alternative process was developed.

optimal values E_i^*, thus realizing a Pareto optimum. The reader is referred to Kaitala *et al.* (1995) for further details.

Although a clear improvement on assuming a global knowledge of the cost functions, this procedure remains unrealistic because it implies that an interregional negotiation occurs at each moment in time, in order to ensure that (2.5) effectively governs the emission levels. This is of course impractical. Moreover, this approach has the further drawback that its time scale is not well defined. Kaitala *et al.* thus propose to modify the dynamics of the process by adjusting the constant K to suit any specific time scale definition. This technique is interesting but it does not resolve the difficulty that the time scale itself could be better defined. Our aim is to present, in the next section, an alternative dynamical model which does not suffer from these problems.

3 A discrete time approach with local information

At variance with the model described in the previous section, we now assume that negotiation occurs at well defined times, which we index by $t = 0, 1, 2, \ldots$. The emission levels and depositions for the i-th region are thus given, at these times, by the quantities $\{E_{i,t}\}_{t=0}^{\infty}$ and $\{Q_{i,t}\}_{t=0}^{\infty}$, where we assume that (2.1) holds for each time period, that is

$$Q_t = Q(E_t) = AE_t + B, \tag{3.1}$$

(where $E_t = (E_{1,t}, \ldots, E_{n,t})^T$ and $Q_t = (Q_{1,t}, \ldots, Q_{n,t})^T$). In this notation, E_0 and Q_0 are the initial emission levels and depositions before the first round of negotiations. We also assume that the parties know their cost functions, not only in an infinitesimal neighbourhood of the current emission levels and depositions, but rather above a certain threshold strictly below these levels. Specifically, each region is assumed to know, for each period t, the values of the emission abatement cost $C_i(E_i)$ for all values of the emission levels

$$F_{i,t} \leq E_i, \tag{3.2}$$

where the lower bounds $F_{i,t}$ satisfy the conditions $0 \leq F_{i,t} < E_{i,t}$ for each i and each t. Similarly, each region is assumed to know its damage function $D_i(Q_i(E))$ for each value of the emissions $\{E_i\}_{i=1}^{n}$ above the same thresholds.

At the t-th negotiation stage, the parties agree on a program to bring their emission levels from E_t to the values E_{t+1} corresponding to a solution of the local optimization problem (2.3) in the domain defined by the constraints (2.1) and (3.2) (Note that $J(\cdot)$ is the sum of convex functions and is therefore convex. Hence the local problem (2.3)–(2.1)–(3.2) is also convex.). Once these emissions levels are attained, the bounds are updated to reflect the new information obtained during the period, according to

$$F_{i,t+1} = \min[F_{i,t}, \tau_{i,t+1} E_{i,t+1}] \tag{3.3}$$

for $i = 1, \ldots, n$, where

$$0 \leq \tau_{i,t+1} \leq \tau \tag{3.4}$$

for some constant $0 \leq \tau < 1$. The parties are then ready for the $(t+1)$-th negotiation stage, and the procedure is repeated. Of course, it may well happen that $E_{t+1} = E_t$ for some t, in which case no further action is requested from the parties and the procedure is then terminated. Note that (3.3) ensures that the domains defined by the constraints (3.2) for successive t are nested, and hence that termination occurs at stage t if $E_{i,t} > F_{i,t}$ for all i.

We then have the following important result, which indicates that the emission levels (and hence depositions) converge to a state corresponding to a Pareto optimum, provided the level set

$$\mathcal{L}_0 = \{E \mid J(E) \leq J(E_0) \ \text{ and } \ E_i \text{ feasible } (i = 1, \ldots, n)\} \tag{3.5}$$

is bounded. This assumption is fairly weak. It is for instance satisfied if the emission levels are not only non-negative but also bounded above (a very plausible situation), or if

$$\lim_{\|E\| \to \infty} \sum_{i=1}^{n} D_i(Q_i(E)) = \infty. \tag{3.6}$$

Note that this latter condition is also natural in our context, since it only reflects the fact that increasing pollutant emission cause increased damage, maybe not locally, but somewhere within the regions under consideration.

Theorem 1 *Under the conditions stated above, the sequence $\{E_t\}$ generated by the procedure converges to a solution of the problem (2.3)–(2.1)–(2.4). Furthermore, this convergence occurs in a finite number of stages if all limiting values of the emissions are all strictly positive.*

Proof. We first show that the sequence $\{E_t\}$ converges to a solution of (2.3)–(2.1)–(2.4) and start by considering the case where the sequence $\{E_t\}$ is infinite.

The boundedness of the level set $\mathcal{L}_0$ and its definition in (3.5) ensure that it is compact. Hence, using (3.4), we may extract a subsequence $\{t_j\}_{j=1}^{\infty} \subseteq \{t\}_{t=1}^{\infty}$ such that $\{E_{t_j}\}_{j=1}^{\infty}$ and $\{\tau_{i,t_j}\}_{j=1}^{\infty}$ $(i = 1, \ldots, n)$ are convergent, with

$$\lim_{j \to \infty} E_{t_j} = \bar{E} \text{ and } \lim_{j \to \infty} \tau_{i,t_j} = \bar{\tau}_i \ (i = 1, \ldots, n). \tag{3.7}$$

If we now define $I \subseteq \{1, \ldots, n\}$ to be the set of indices such that $E_{i,t} = F_{i,t-1}$ for infinitely many t_j, we see that this set must contain at least one element, otherwise the procedure would stop and the convergence would be finite. We then deduce that, for each $i \in I$,

$$\bar{E}_i = \lim_{j \to \infty} E_{i,t_j} = \lim_{j \to \infty} F_{i,t_j-1} \leq \lim_{j \to \infty} F_{i,t_{j-1}} \leq \lim_{j \to \infty} \tau_{i,t_{j-1}} E_{i,t_{j-1}} = \bar{\tau}_i \bar{E}_i, \tag{3.8}$$

where we have used (3.3). But $\bar{\tau}_i \leq \tau < 1$ by (3.4), and thus (2.4) and (3.8) imply that

$$\bar{E}_i = 0 \text{ for each } i \in I. \tag{3.9}$$

If we now examine the first order optimality conditions for the local problems (2.3)–(2.1)–(2.4) at each stage, we obtain that

$$\frac{\partial J}{\partial E_i}(E_{t_j}) \left\{ \begin{array}{ll} \geq 0 & \text{if } E_{i,t_j} = F_{i,t_j-1}, \\ = 0 & \text{if } E_{i,t_j} > F_{i,t_j-1}. \end{array} \right. \tag{3.10}$$

In the limit, we thus deduce from (3.10) and the definition of I that

$$\frac{\partial J}{\partial E_i}(\bar{E}) = \nabla J(\bar{E})_i \begin{cases} \geq 0 & i \in I. \\ = 0 & i \notin I. \end{cases} \tag{3.11}$$

Let us now denote by E^* a solution of the global problem (2.3)–(2.1)–(2.4), which obviously ensures that $J(\bar{E}) \geq J(E^*)$. Now, if $J(\bar{E}) > J(E^*)$, then we would have that

$$\begin{array}{rcl} 0 > J(E^*) - J(\bar{E}) & \geq & \nabla J(\bar{E})^T(E^* - \bar{E}) \\ & = & \sum_{i \in I} \nabla J(\bar{E})_i(E_i^* - \bar{E}_i) \\ & = & \sum_{i \in I} \nabla J(\bar{E})_i E_i^* \geq 0, \end{array} \tag{3.12}$$

where we successively used the convexity of $J(\cdot)$, (3.11) and (3.9). But (3.12) is impossible, and we obtain therefore that $J(\bar{E}) = J(E^*)$ as desired.

If, on the other hand, the sequence $\{E_t\}$ is finite, then we have that, for some t and for all i, $E_{i,t+1} = E_{i,t} = \bar{E}_i$, and thus

$$0 \leq F_{i,t} \leq \tau \bar{E}_i < \bar{E}_i, \tag{3.13}$$

and the solution of the local program (2.3)–(2.1)–(3.2) is not constrained by any of the bounds (3.2): it is therefore also a solution of the global program (2.3)–(2.1)–(2.4), which completes the proof of the first statement of the theorem.

We now prove the second statement and assume, for the purpose of a contradiction, that the sequence $\{E_t\}$ is infinite. As in the first part of the proof, we obtain that (3.9) for some non-empty set I, which is impossible if all limiting values of the emissions are strictly positive. Hence, this latter condition implies that the sequence $\{E_t\}$ is finite and the theorem is proved. □

4 An application to Northern European negotiations about acid rain

We now examine the impact of the model and theory developed in the previous section on the Kaitala *et al* (1995) dynamic version of the "acid rain game" in Northern Europe. Specifically, the problem is for Finland (divided in three regions), three regions of Russia and Estonia to agree on a program for reducing SO_2 emissions, which should limit acid rain and its associated damages. This problem had already been studied by Kaitala and Podjola (1994). The emission abatement costs are assumed to be, in the interval $[0, \tilde{E}_i]$, of the form

$$C_i(E_i) = \gamma_i + \alpha_i(\tilde{E}_i - E_i) + \beta_i(\tilde{E}_i - E_i)^2 \tag{4.1}$$

for each $i = 1, \ldots, n$ while the damage functions may be written as

$$D_i(Q_i) = \pi_i Q_i \tag{4.2}$$

for each i. Both these costs are expressed in millions of 1987 Finnish Marks (MFIM) and the depositions are expressed in thousands of tons per year (KT/Y). The parameters α_i, β_i, γ_i, π_i

and $\tilde{E}_i$ are positive. Their values are given in Table 1, together with that of the initial levels E_0, Q_0 and B in 1987. The initial state is the same as that considered by Kaitala *et al* (1995)[2]. The transport coefficients (the matrix A) is given in Table 2. The information thresholds for the costs and damage functions are determined using the formula (3.3) where $\tau_{i,t} = 0.95$ for all i and t, which means that these functions are known for all emission levels above 95% of the current ones.

i	Region	$E_{i,0}$	$Q_{i,0}$	B_i	α_i	β_i	γ_i	$\tilde{E}_i$	π_i
1	Northern Finland	5	46	26	10.0	2.093	5.9	5	50
2	Central Finland	60	98	59	3.8	0.172	33.0	60	8.9
3	Southern Finland	97	66	35	4.6	0.068	53.6	97	15.6
4	Kola:	350	131	27					2.6
	• $98 \leq E_4 \leq 350$				1.0	0.000	0.0	350	
	• $0 \leq E_4 \leq 98$				1.0	0.077	252.0	98	
5	Karelia	85	95	50	4.0	0.045	0.0	85	11.6
6	St Petersburg	112	88	46	6.0	0.051	0.0	112	20.2
7	Estonia:	104	60	32					2.8
	• $60 \leq E_7 \leq 104$				2.0	0.000	0.0	104	
	• $0 \leq E_7 \leq 60$				2.0	0.191	88.0	60	

Table 1: Parameters and initial levels

	Emitting region (i)						
Receiving region (j)	NF	CF	SF	Ko	Ka	SP	Es
Northern Finland (NF)	0.200	0.017	0.010	0.046	0.012	0.000	0.000
Central Finland (CF)	0.000	0.300	0.062	0.011	0.047	0.036	0.029
Southern Finland (SF)	0.000	0.017	0.227	0.003	0.000	0.027	0.038
Kola (Ko)	0.000	0.017	0.000	0.286	0.023	0.009	0.000
Karelia (Ka)	0.000	0.033	0.031	0.017	0.318	0.045	0.019
St Petersburg (SP)	0.000	0.017	0.031	0.003	0.012	0.268	0.058
Estonia (Es)	0.000	0.000	0.031	0.000	0.000	0.018	0.221

Table 2: Transport coefficients in 1987

Table 3 and Figure 1 show the evolution of the SO_2 emission levels that result from the procedure described in the previous section. As shown by Table 3, 29 negotiation stages are necessary, given our assumptions, to reach the Pareto optimum, which coresponds to that reported

[2]Which is a Nash equilibrium of some non cooperative game assumed to occur between Finland (with its three regions merged) and the USSR of 1987 (whose four regions are also merged)

by Kaitala *et al* (1995)[3]. This number of stages could of course be reduced if the values chosen for $\tau_{i,t}$ were smaller. The underlined entries in Table 3 (which corresponds to the vertical lines of Figure 1) show that regions reach the optimum in very different times. Northern Finland is already at the optimum at the beginning. Central Finland reaches it after one period, Southern Finland and St Petersburg after 2, Karelia after 3, Estonia after 12 and Kola after 29. If we now compare the initial and final states, we note that the reductions vary considerably between regions. While the emissions of Central and Southern Finland, Karelia and St Petersburg are slightly reduced, the reduction is much more substantial for Kola and Estonia.

One observes that Northern Finland doesn't reduce its emissions, because as it appears from matrix A's first column, its pollution doesn't affect the other regions. It has then only to care of its emissions' impact on its own environment, what it already does at the initial state, since it is supposed to be a Nash equilibrium. One observes either that once at their optimal level, a region's emissions stay constant afterwards. This follows from the linearity of the damage functions (cfr. (4.2)). Indeed, first order conditions at time t show, after substitution of (4.1) and (4.2) that the latter is separable, in the sence that emissions of a region are independant of the others. This property would not verify if the D_i's were not linear.

Figure 1: Evolution of the SO_2 emissions

[3] Because of the linear segment of Kola and Estonia's costs functions, one cannot *a priori* be sure that this optimum is unique. Nevertheless, as it is obtained on the quadratic segment of these functions, it is indeed unique.

	NF	CF	SF	Ko	Ka	SP	Es
0	5.0000	60.0000	97.0000	350.0000	85.0000	112.0000	104.0000
1	5.0000	57.7597	92.1500	332.5000	80.7500	106.4000	98.8000
2	5.0000	57.7597	89.1243	315.8750	76.7125	104.7077	93.8600
3	5.0000	57.7597	89.1243	300.0813	73.6603	104.7077	89.1670
4	5.0000	57.7597	89.1243	285.0772	73.6603	104.7077	84.7086
5	5.0000	57.7597	89.1243	270.8233	73.6603	104.7077	80.4732
6	5.0000	57.7597	89.1243	257.2822	73.6603	104.7077	76.4496
7	5.0000	57.7597	89.1243	244.4181	73.6603	104.7077	72.6271
8	5.0000	57.7597	89.1243	232.1972	73.6603	104.7077	68.9957
9	5.0000	57.7597	89.1243	220.5873	73.6603	104.7077	65.5459
10	5.0000	57.7597	89.1243	209.5579	73.6603	104.7077	62.2686
11	5.0000	57.7597	89.1243	199.0800	73.6603	104.7077	59.1552
12	5.0000	57.7597	89.1243	189.1260	73.6603	104.7077	57.7671
13	5.0000	57.7597	89.1243	179.6697	73.6603	104.7077	57.7671
14	5.0000	57.7597	89.1243	170.6862	73.6603	104.7077	57.7671
15	5.0000	57.7597	89.1243	162.1519	73.6603	104.7077	57.7671
16	5.0000	57.7597	89.1243	154.0443	73.6603	104.7077	57.7671
17	5.0000	57.7597	89.1243	146.3421	73.6603	104.7077	57.7671
18	5.0000	57.7597	89.1243	139.0250	73.6603	104.7077	57.7671
19	5.0000	57.7597	89.1243	132.0738	73.6603	104.7077	57.7671
20	5.0000	57.7597	89.1243	125.4701	73.6603	104.7077	57.7671
21	5.0000	57.7597	89.1243	119.1966	73.6603	104.7077	57.7671
22	5.0000	57.7597	89.1243	113.2367	73.6603	104.7077	57.7671
23	5.0000	57.7597	89.1243	107.5749	73.6603	104.7077	57.7671
24	5.0000	57.7597	89.1243	102.1962	73.6603	104.7077	57.7671
25	5.0000	57.7597	89.1243	97.0864	73.6603	104.7077	57.7671
26	5.0000	57.7597	89.1243	92.2320	73.6603	104.7077	57.7671
27	5.0000	57.7597	89.1243	87.6204	73.6603	104.7077	57.7671
28	5.0000	57.7597	89.1243	83.2394	73.6603	104.7077	57.7671
29	5.0000	57.7597	89.1243	82.1215	73.6603	104.7077	57.7671

Table 3: Evolution of the SO_2 emissions

We now consider the total costs incurred by each region in the transition from the initial Nash equilibrium to the final Pareto optimum. More precisely, we report in Table 4 the values

$$J_i(E^*) - J_i(E_0) = C_i(E^*) - C_i(E_0) + D_i(E^*) - D_i(E_0)$$

for $i = 1, \ldots, n$, where E^* is the optimal emission level reached at stage 29. The table also reports the same costs aggregated for the whole of Finland, the whole of the 3 regions of Russia and Estonia. Figure 2 presents the evolution of these costs over the 29 negotiations stages.

Finland			Russia			Estonia
NF	CF	SF	Ko	Ka	SP	Es
-628.8	-46.5	-31.1	87.6	-61.5	-71.6	64.2
-706.4			-45.5			64.2

Table 4: Total costs $(J_i(E^*) - J_i(E_0))$ per region and country (MFIM)

These results show that the emissions reduction program does considerably profit to Finland, does also profit to Russia but costs to Estonia. If one considers regions instead of countries, cooperation appears to be profitable to all regions except Kola and Estonia. The reasons are twofold: first, these regions are those that reduce most their emissions; second, their marginal damage coefficient (cfr. the π_i in Table 1) being by far the leasts, they profit much less from the emissions reduction via their damage functions. The cooperation of Kola and Estonia in such a program of cooperation is thus unlikely, unless some financial transfers can be devised between the regions, that would compensate for these incurred costs. The definition of such a strategy is the object of the next section.

Figure 2: Evolution of total costs per region (MFIM)

5 Cooperation and financial transfers

The main idea is that the aggregate reduction of total costs $J(E_0) - J(E^*)$ (also called the "ecological surplus") can be used as a resource to share between the regions in order to induce their cooperation within the emission reduction program. This surplus is, in the example of the previous section, equal to 688 MFIM per year, that is 9% of the initial total cost, a very respectable amount. It is more than sufficient to offer to Estonia a financial transfer that would reduce its costs below the level supported initially, while maintaining considerable advantages for the other regions.

However, the surplus $J(E_0) - J(E^*)$ is only known at the end of the reduction program, once the emission levels E^* are achieved. Thus it cannot be used in any practical negotiation process between the parties during the program. Instead, one needs a key to share whatever benefit is achieved at a given negotiation stage between the regions, in order to ensure that each of them continues to cooperate within the program. The aim of this section is to show that such financial transfers can indeed be found.

Let us start from the fact that the total surplus obtained between two negotiation stages is the sum of the different regions' gains or losses, that is

$$\Delta J_t = J_{t+1} - J_t = \sum_{i=1}^{n} \Delta J_{i,t} = \sum_{i=1}^{n} [\Delta C_{i,t} + \Delta D_{i,t}]. \tag{5.1}$$

Because of the linear form of the damage function (4.2), we obtain that

$$\Delta D_{i,t} = \pi_i \sum_{j=1}^{n} a_{ij} \Delta E_{j,t}. \tag{5.2}$$

Combining (5.1) and (5.2), we see that

$$\begin{aligned} \Delta J_t &\leq \sum_{i=1}^{n} \Delta C_{i,t} + \sum_{i=1}^{n} \pi_i \sum_{j=1}^{n} a_{ij} \Delta E_{j,t} \\ &= \sum_{j=1}^{n} [\Delta C_{j,t} + \Delta E_{j,t} \sum_{i=1}^{n} a_{ij} \pi_i] = \sum_{j=1}^{n} \Delta G_{j,t}, \end{aligned} \tag{5.3}$$

defining the $\Delta G_{j,t}$. These quantities can be seen as the total surplus obtained when region j decreases its emissions

We have now the following result.

Theorem 2 *At each stage t of the negotiation process and for all regions ($j = 1, \ldots, n$), one has that*

$$\Delta G_{j,t} \leq 0 \tag{5.4}$$

Proof. For stage t, consider the functions

$$G_j(E_j) = C_j(E_j) + E_j \sum_{i=1}^{n} a_{ij} \pi_i, \; j = 1, ..., n, \tag{5.5}$$

This definition implies that

$$\Delta G_{j,t} = G_j(E_{j,t+1}) - G_j(E_{j,t}) \tag{5.6}$$

because of (5.3), and the convexity of G_j in E_j also yields that

$$G_j(E_{j,t+1}) - G_j(E_{j,t}) \leq G'_j(E_{j,t+1})[E_{j,t+1} - E_{j,t}]. \tag{5.7}$$

Now, the derivative of G_j is given by

$$G_j'(E_j) = C_j'(E_j) + \sum_{i=1}^{n} a_{ij}\pi_i \tag{5.8}$$

and the first order optimality conditions of problem (2.3)–(2.1)–(3.2) at stage $t+1$ imply that

$$G_j'(E_{j,t+1}) = C_j'(E_{j,t+1}) + \sum_{i=1}^{n} a_{ij}\pi_i \geq 0 \tag{5.9}$$

when $E_{j,t+1} \leq E_{j,t}$ and

$$G_j'(E_{j,t+1}) = C_j'(E_{j,t+1}) + \sum_{i=1}^{n} a_{ij}\pi_i = 0 \tag{5.10}$$

otherwise, because the emissions are only bounded from below. Combining (5.6), (5.7),(5.9)and (5.10) then yields (5.4). □

Using this result, we may then specify for each region i and each negotiation stage t, a financial transfer $T_{i,t}$ (negative if received by i or positive if paid) given, for $i = 1, \ldots, n$, by

$$\Delta T_{i,t} = -\Delta C_{i,t} - \Delta D_{i,t} + \sum_{j} \delta_{ij} \Delta G_{j,t}, \tag{5.11}$$

where

$$0 \leq \delta_{ij} \leq 1,\ \forall i, j \text{ and } \sum_{i=1}^{n} \delta_{ij} = 1,\ \forall j. \tag{5.12}$$

The first two terms of (5.11) are equivalent to levying on region i its gain on total cost, while the third term corresponds to returning to the region a fraction δ_{ij} of each of the surpluses $\Delta G_{j,t}$. One immediately verifies that the budget of these transfers is balanced at each period, namely that

$$\sum_{i=1}^{n} \Delta T_{i,t} = 0,\ \forall t. \tag{5.13}$$

Moreover, as the total cost for region i with transfers is

$$J_i^T = C_i(E_i) + D_i(E_i) + T_i, \tag{5.14}$$

we have then that

$$\Delta J_i^T = \Delta C_i + \Delta D_i + \Delta T_i = \sum_{j=1}^{n} \delta_{ij} \Delta G_{j,t} \leq 0, \tag{5.15}$$

for $i = 1, ..., n$, because of (5.4). In other words, the total cost of each region decreases at each negotiation stage. This property, called *individual rationality*, provides a minimum cooperative character to the sequence of negotiations.

Of course, conditions (5.12) do not define the transfers in a univoque manner. All matrices of positive parameters δ_{ij} whose columns sum up to one are adequate. Following Chander and Tulkens (1994) and Kaitala *et al* (1995), we propose to choose

$$\delta_{ij} = \frac{\partial D_i / \partial E_j}{\sum_{k=1}^{n} \partial D_k / \partial E_j} = \frac{a_{ij}\pi_i}{\sum_{k=1}^{n} a_{kj}\pi_k}. \tag{5.16}$$

These values verify (5.12) and thus ensure the properties of balanced budget (5.13) and individual rationality (5.15).

With linear damage functions, it is also possible to derive certain results of *coalitional rationality*, ensuring that there is no advantage for a coalition of regions to form and cooperate in a framework more restricted than the full inter-regional cooperation considered here. We refer the interested reader to Germain, Toint and Tulkens (1995) for a full statement and a proof of this property.

6 The transfers in the example

The application of formulae (5.13) and (5.16) to the cooperation problem between Finland, Russia and Estonia leads to the evolution of transfers illustrated by Figure 3. Recall that $T_{i,t} \geq 0 (\leq 0)$ means that region i pays (receives) transfers. Estonia and Kola are the principal recipients of transfers, i.e. the regions that reduce most their emissions and whose global costs *without* transfers increase with international cooperation (see Figure 2). The principal payer is Northern Finland, the region that profits most from cooperation. Figure 3 also shows that Southern Finland and Karelia benefit marginally of transfers during the first stages, but they soon become payers, as St. Petersburg and Northern and Central Finland.

Figure 3: Evolution of transfers per region (MFIM)

The presence of transfers doesn't imply that the benefits of cooperation are evenly distributed among regions, as shown (in absolute terms) by the third column of Table 5. The fact that the total cost of each region decreases illustrates the property of individual rationality of the negotiation process with transfers. The last column of Table 5 shows that the distribution of the surplus is also uneven in relative terms. Because of its low initial costs (due to its very low marginal damage), Kola obtains, taking the transfers into account, the most important relative reduction of total costs, followed by Northern Finland. At the national level however, one observes that the distribution of the surplus is not so uneven, and that even without tranfers, Russia is interested to collaborate.

	$J_i(E^*) - J_i(E_0)$	$T_i(E^*)$	$J_i^T(E^*) - J_i^T(E_0)$	$\frac{J_i^T(E^*) - J_i^T(E_0)}{J_i^T(E_0)}$
NF	-628.8	203.2	-425.6	-18.4 %
CF	-46.5	23.3	-23.2	-2.6 %
SF	-31.1	11.6	-19.5	-1.8 %
Finland	-706.4	238.1	-468.3	-10.9%
Ko	87.6	-224.6	-136.9	-40.3%
Ka	-61.5	17.2	-44.3	-4.0 %
SP	-71.6	41.7	-29.9	-1.7 %
Russia	-45.5	-165.7	-211.1	-6.6 %
Es	64.2	-72.5	-8.3	-5.0 %
Total	-687.7	0	-687.7	-8.9 %

Table 5: Reduction cost figures without (column 1) and with transfers (column 3) (MFIM)[4].

As formulas (5.11) and (5.16) indicate, the share of the benefits of cooperation is entirely determined by the fractions $(\delta_{1j}, \ldots, \delta_{nj})$ of each of the ecological surpluses $G_j(E_{jf}^*) - G_j(E_{j0})(j = 1, \ldots, n)$, where $G_j(E_j)$ is defined by (5.5). A region i will benefit from the reduction of region j's emissions the more are important (i) j's reduction, (ii) i's marginal damage cost π_i and (iii) the fraction a_{ij} of j's emissions deposited in i. In particular, a region reducing stongly its emissions, but for which $\pi_i = 0$, would have from (5.11) and (5.16) a benefit equal to zero, its cost of depollution being however covered — no more — by received transfers.

In the case of our simulation, Northern Finland doesn't reduce its emissions but benefits strongly from saving of damage costs. As it is polluted by Central and Southern Finland and mainly by Kola - the last lowering deeply its emissions, Northern Finland pays a lot for these reductions because its marginal damage cost is very big ($\pi_1 = 50$). At the other extreme, Estonia doesn't profit very much from cooperation. This is due to the fact that its marginal damage cost is low ($\pi_7 = 2.8$ only), and that the coefficients a_{7j} $(j = 1, \ldots, n)$ are low and only positive for emitting regions that do not reduce very much their emissions between the initial and final states (Southern Finland and St Petersburg).

From a strategic point of view (i.e. to prevent coalitions), Kola and Northern Finland are thus the most important partners to convince to participate to cooperation rather than to stay

[4] In this table, subscript 0 refers to the initial state and superscript * to the final state.

as free riders: the first because its emissions reduction is the most important for everybody, the second because it agrees to pay a lot for all emissions reduction. In the present context, this means allowing them to obtain an important share of the total ecological surplus induced by cooperation. This explains the results of columns 3 and 4 of Table 5.

7 Conclusion

We have proposed and analyzed a dynamic process, intended to model negotiations between several countries or regions bearing on the reduction of transboundary pollution. The process ensures that the Pareto optimum is attained in a finite number of negotiation stages, each of which consisting of a period of negotiation on the emission reductions, based on limited information, followed by a period during which emissions are effectively reduced. We have also shown that international financial transfers can be found, ensuring that costs of reduction are distributed in such a way that cooperation is profitable for each region.

The authors are however well aware that the proposed process has its limits. Realism suggests further developments. First, the interval of time between two stages of negotiation is currently exogenous: it should be integrated in the objective. Secondly, the thresholds up to which the abatement and damage cost functions are known could be considered as part of the negotiation process itself. A strategic analysis on this point would bring our work in direct connection with the classical literature on revelation of preferences and costs. Finally, the analysis could be extented to stock pollutants, where permanent effects of depositions are present. This would require to reformulate the objective in intertemporal terms. One can find in Mäler (1992) an interesting attempt in that direction.

References

Arrow K. and Hurwicz L. (eds). (1977). *Studies in Resource Allocation Processes.* Cambridge University Press, Cambridge U.K..

Champsaur P., Drèze J. and Henry C. (1977). Stability theorems with economic applications. *Econometrica* 45(2): p.273-294.

Chander P. and Tulkens H. (1992). Theoretical foundations of negotiations and cost sharing in transfrontier pollution problems. *European Economic Review* 36(2/3): p.288-299.

Chander P. and Tulkens H. (1991). Stategically stable cost sharing in an economic-ecological negotiation process. In K. G. Mäler, editor, *International Environmental Problems*, Dordrecht, NL, Kluwer Academic Publishers (forthcoming).

Drèze J. and de la Vallée Poussin D. (1971). A tâtonnement process for public goods. *Review of Economic Studies* 38: p.133-150.

Germain M., Toint Ph. anf Tulkens H. (1995). Calcul économique itératif pour les négociations internationales sur les pluies acides entre la Finlande, la Russie et l'Estonie. Dicussion paper nr 9417 (revised august 1995), Institut de Recherches Economiques et Sociales, Université de Louvain.

Kaitala V., Mäler K. and Tulkens H. (1995). The acid rain game as a resource allocation process, with application to negotiations between Finland, Russia and Estonia. *The Scandinavian Journal of Economics* 97(2): p.325-344.

Kaitala V. and Podjola M. (1994). Acid rain and international environmental aid: a case study of transboundary pollution between Finland, Russia and Estonia. In K. Mäler, editor, *International Environmental Problems*, Dordrecht, NL, Kluwer Academic Publishers.

Mäler K. (1989). The acid rain game. In H. Folmer and E. van Ierland, editors, *Valuation Methods and policy Making in Environmental Economics*, Amsterdam, NL, Elsevier.

Mäler K. (1992). Critical loads and international environmental cooperation. In R. Pethig, editor, *Conflicts and cooperation in managing environmental resources*, p.71-81, Berlin, Springer Verlag.

Malinvaud E. (1970-71). Procedures for the determination of a program of collective consumption. *European Economic Review* 2: p.187-217.

Tulkens H. (1979). An economic model of international negotiations relating to transfrontier pollution. Chapter 16 (p.199-212) in K. Krippendorff, editor, *Communication and Control in Society*, Gordon and Breach Science Publishers, New York.