Incentive Equilibrium Strategies and Welfare Allocation in a Dynamic Game of Pollution Control

Steffen Jørgensen
Department of Management, University of Southern Denmark, Odense University.
e-mail: stj@sam.sdu.dk

Georges Zaccour
GERAD and HEC, Montréal, Canada
e-mail:georges.zaccour@hec.ca

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Abstract

The paper considers two neighboring countries wishing to make a joint effort to control pollution emission. We use a differential game model that includes emission and investment in abatement technology as control variables. First, a coordinated solution that maximizes joint welfare is derived. Then we show that this outcome can be achieved as an incentive equilibrium in which each country uses an emission strategy that is linear in the other country's emission level. Further, we study the bargaining problem for allocating the joint welfare between the two countries, where the status quo is given by the open-loop Nash equilibrium. Finally, we design a mechanism for allocating over time the individual total costs which ensures that the players will stick to the joint optimization solution for the whole duration of the game.

Key words: Pollution Control, Differential Games, Incentive Equilibrium, Time-Consistency.

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1 Introduction

Differential games and optimal control methodologies have been applied by many scholars during the last decade to study environmental problems (see e.g. Van der Ploeg and de Zeeuw (1992), Dockner and Van Long (1993), Martin et al. (1993), Kaitala and Pohjola (1995), Kaitala et al. (1995), Haurie and Zaccour (1995), Germain et al. (1997, 1998)). It has been shown in this literature that coordination of countries' emission strategies leads to a lower total level of pollution and to a higher total welfare than non cooperative emission strategies. A focal point of these studies is how to insure that the countries involved in the pollution control negotiations will indeed implement the coordinated emission policies. This problem stems from the fact that joint optimization (cooperative or coordinated solution) guarantees collective rationality but not necessarily individual. Indeed, it may be the case that some players get a lower total welfare in the joint optimization solution than in the non cooperative scenario. If the only issue is how to allocate the total welfare, as it is typically the case in a static setting, it is easy to reestablish individual rationality. For instance, one may allocate the total cooperative welfare using any solution concept of cooperative game theory (e.g. Shapley value, core) where individual rationality is guaranteed. This approach is followed in e.g. Filar and Gaertner (1997) where the total emission reduction is allocated to four different regions by means of Shapley value. In a dynamic context, we still need to allocate the total welfare. There is however a difficulty which stems from the fact that the agreed upon sharing rule at initial time may not meet the individual rationality requirement at a later date (see Haurie (1976)). If one wishes that, at any intermediate date, each player finds it individually rational to stick to cooperation for the remaining horizon, then an intertemporal allocation mechanism is needed. This dynamic rationality principle has been dealt with in the literature in different manners.

A first option is to assume that the implementation of cooperative strategies is binding. Under these circumstances, there is no issue. A second option is to design a mechanism which supports the cooperative agreement as an equilibrium. Yet another approach is to use the concepts of agreeability (Kaitala and Pohjola (1990)) and time-consistency (Petrosjan (1993, 1997), Petrosjan and Zaccour (1999)). They require, at any intermediate date, that any player's cooperative-welfare-to-go (including possibly a suitable side payment) be higher than its non cooperative counterpart for the remaining horizon, along the optimal state trajectory. The assumption here is that the game has been played cooperatively till that date. Finally, one may aim to achieve an instantaneous dynamic rationality result, that is at any instant of time each player's instantaneous cooperative outcome dominates his instantaneous non cooperative one. Note that agreeability and time-consistency do not necessarily imply instantaneous dynamic rationality, nor the other way around.

This paper considers two neighboring countries that wish to coordinate their emission strategies to control pollution. We first determine optimal emission levels under cooperation (joint maximization of welfares) and non cooperation. In the latter case, we look for an open-loop Nash equilibrium. The corresponding outcomes will play the role of the status quo point in the cooperative welfare sharing problem. It is shown that it is possible to achieve the cooperative emission levels as an incentive equilibrium. To construct such equilibrium, we assume that each player determines his incentive strategy as a linear function of neighbor's one. Finally, we design an allocation mechanism of total individual welfares that insures instantaneous dynamic individual rationality.

The rest of the paper is organized as follows. In Section 2 we introduce a simple ecological economics model. In Section 3 we derive the joint maximization solution and an open-loop Nash equilibrium. In Section 4 we construct an incentive equilibrium. In Section 5 we deal with the issue of sharing of the joint optimal welfare and design an instantaneous individually rational allocation mechanism. In Section 6 we conclude.

2 The ecological economics model

Consider two neighboring countries (or regions) whose industrial activities create pollution as an undesirable by-product. For $i = 1, 2$ denote by $Y_i(t)$ the rate of production in country i at time $t \in [0, T]$, and let $U_i(Y_i(t))$ represent the instantaneous utility derived from producing at the rate $Y_i(t) \geq 0$. The utility functions are increasing, strictly concave and satisfy $U'(0) = +\infty$. The latter assumption implies that zero production is unprofitable. Denote by $E_i(t)$ the rate of emission resulting from production of region i and let $K_i(t)$ represent region i's stock of abatement capital by time t. The emission rate is given by $E_i(t) = \alpha_i(K_i(t))Y_i(t)$ (c.f. Van der Ploeg and de Zeeuw (1992)). Thus, the emission rate is proportional to current output $Y_i(t)$. The proportionality factor $\alpha_i(K_i(t))$ decreases with the size of the stock of abatement capital, that is, $\alpha_i'(K_i(t)) < 0$ and to account for decreasing returns in the abatement activities we assume $\alpha_i^{''}(K_i(t)) > 0$. Region i can raise its stock of abatement capital through investment. Denote the rate of physical investment by $I_i(t)$ and the cost incurred by $C_i(I_i(t))$. The investment cost function is increasing and convex. The capital stocks evolve according to the standard dynamics

$$\dot{K}_i(t) = I_i(t) - \mu_i K_i(t), \qquad K_i(0) = K_i^0 \geq 0 \text{ given} \tag{1}$$

where $\mu_i > 0$ is a constant rate of depreciation.

The stock of pollution $S(t)$ evolves according to

$$\dot{S}(t) = E_1(t) + E_2(t) - \delta S, \quad S(0) = S^0 \geq 0 \text{ given} \tag{2}$$

in which $\delta > 0$ is a constant decay rate of pollution. Each country incurs a damage cost given by $D_i(S(t))$. This cost is increasing and convex. The objective of region i is to maximize its social welfare function given by

$$W_i = \int_0^T (U_i(Y_i(t)) - C_i(I_i(t)) - D_i(S(t))\,dt \quad \text{subject to (1)-(2)} \tag{3}$$

To illustrate the design of particular incentive strategies, we need to specify functional forms for cost, emission and utility functions. Omitting the time argument, the following ones satisfy the assumptions made above

$$U_i(t) = LogY_i, \quad C_i(I_i) = \frac{1}{2}c_i I_i^2, \quad \alpha_i(K_i) = \sigma_i e^{-\beta_i K_i}, \quad D_i(S) = \varphi_i S \tag{4}$$

Given the assumed link between production and emission, the optimization program of player i can be written as follows

$$\begin{aligned} \max W_i &= \int_0^T \left(LogE_i + \beta_i K_i - \frac{1}{2}c_i I_i^2 - \varphi_i S \right) dt \\ & \quad \text{subject to (1)-(2)} \end{aligned} \tag{5}$$

Some remarks are in order regarding the model. A constant term ($-Log\sigma_i$) should appear in the objective and has been omitted since it does not affect the derivation of optimal and equilibrium results. Also the results would remain qualitatively unaltered if one incorporates the following features: (i) adding salvage values as functions of the stocks of abatement capacities and pollution at terminal date, (ii) multiplying the emission rates in the pollution dynamics by different constants to account for differential effects on pollution accumulation, (iii) scaling by a constant the utility function, (iv) adding a linear component to the investment cost function and (v) assuming a more realistic damage function, e.g. a quadratic one. It must be stressed for the moment that our model still captures two of the main ingredients of the debate on pollution reduction, namely that countries do not necessarily emit at the same rate and that emissions by any country affect the common environment.

3 Cooperative solution and Nash equilibrium

In this section we derive the joint optimization solution and identify an open-loop Nash equilibrium. The first solution will provide optimal emission levels and the total welfare to share between the two countries. The open-loop Nash equilibrium will be used as the status quo point in this sharing problem.

3.1 Cooperative solution

We assume that the cooperative solution is obtained as the result of the joint optimization problem

$$\begin{aligned} \max(W_1 + W_2) &= \sum_{i=1}^{2} \int_0^T \left(LogE_i + \beta_i K_i - \frac{1}{2}c_i I_i^2 - \varphi_i S \right) dt \\ & \quad \text{subject to (1)-(2)} \end{aligned} \tag{6}$$

The Hamiltonian is defined by

$$\begin{aligned} H &= \sum_{i=1}^{2} \left(LogE_i + \beta_i K_i - \frac{1}{2}c_i I_i^2 - \varphi_i S + \lambda_i (I_i - \mu_i K_i \right) \\ & \quad + \theta(E_1 + E_2 - \delta S) \end{aligned} \tag{7}$$

where λ_i and θ are the adjoint variables. Optimality conditions include

$$\dot{S} = E_1 + E_2 - \delta S, \quad S(0) = S^0 \tag{8}$$

$$\dot{\theta} = \delta\theta + (\varphi_1 + \varphi_2), \quad \theta(T) = 0 \tag{9}$$

$$\dot{K}_i = I_i - \mu_i K_i, \qquad K_i(0) = K_i^0, \quad i = 1,2 \tag{10}$$

$$\dot{\lambda}_i = \mu_i \lambda_i - \beta_i, \quad \lambda_i(T) = 0, \quad i = 1,2 \tag{11}$$

$$E_i = -\frac{1}{\theta} \tag{12}$$

$$I_i = \frac{\lambda_i}{c_i} \tag{13}$$

We identify the cooperative solution with the superscript c. Solving the differential equations (9) and (11) leads to

$$\theta^c = -\frac{(\varphi_1 + \varphi_2)}{\delta}\left(1 - e^{-\delta(T-t)}\right) \tag{14}$$

$$\lambda_i^c = \frac{\beta_i}{\mu_i}\left(1 - e^{-\delta(T-t)}\right), \quad i = 1,2 \tag{15}$$

As expected, θ^c is negative (pollution stock is a "bad" one) and λ_i^c is positive (abatement capacity is a "good" stock). It can easily be checked that θ^c and λ_i^c are respectively decreasing and increasing over time. Inserting θ^c and λ_i^c into (12) and (13) respectively leads to the following optimal emission and investment policies

$$E_i^c = \frac{\delta}{(\varphi_1 + \varphi_2)\left(1 - e^{-\delta(T-t)}\right)}, \quad i = 1,2 \tag{16}$$

$$I_i^c = \frac{\beta_i}{c_i \mu_i}\left(1 - e^{-\delta(T-t)}\right), \quad i = 1,2 \tag{17}$$

As is readily seen, emission depends on both players marginal damage costs and investment is determined such that its marginal cost is equal to the shadow price of abatement stock. Given the optimal emission and investment policies, one can solve for the optimal abatement and pollution stocks.

Denote by $W^c = W_1^c + W_2^c$ the optimal cooperative outcome, where W_i^c is obtained by inserting the optimal values of control and state variables in player's i objective functional. We shall deal with the issue of distributing this joint welfare later on.

3.2 Nash equilibrium

To identify an open-loop Nash equilibrium, write down the Hamiltonians:

$$\begin{aligned} H^i = & \left(Log E_i + \beta_i K_i - \frac{1}{2} c_i I_i^2 - \varphi_i S + \lambda_i (I_i - \mu_i K_i\right) \\ & + \theta_i (E_1 + E_2 - \delta S), \quad i = 1,2 \end{aligned} \tag{18}$$

Notice that formally we should insert in player's i Hamiltonian the r.h.s. of player's j abatement stock dynamics multiplied by an adjoint variable. Due to the decoupling of investment and abatement stock variables of the two players, this is not necessary. Assuming an interior solution, sufficient equilibrium conditions are the following

$$\dot{S} = E_1 + E_2 - \delta S, \quad S(0) = S^0 \tag{19}$$

$$\dot{\theta}_i = \delta\theta_i + \varphi_i, \quad \theta_i(T) = 0 \tag{20}$$

$$\dot{K}_i = I_i - \mu_i K_i, \qquad K_i(0) = K_i^0, \quad i = 1,2 \tag{21}$$

$$\dot{\lambda}_i = \mu_i\lambda_i - \beta_i, \quad \lambda_i(T) = 0, \quad i = 1,2 \tag{22}$$

$$E_i = -\frac{1}{\theta_i} \tag{23}$$

$$I_i = \frac{\lambda_i}{c_i} \tag{24}$$

We identify Nash equilibrium by the superscript N. As one can notice, the equilibrium investment strategy and the multiplier of the abatement capacity are the same as the one obtained in the cooperative solution. The implication is that open-loop Nash equilibrium investment strategies are Pareto-optimal. This is due to the structure of our model where there is no interaction between players' investment decisions. Therefore,

$$I_i^N = \frac{\beta_i}{c_i\mu_i}\left(1 - e^{-\delta(T-t)}\right), \quad i = 1,2 \tag{25}$$

The interpretation of investment strategy is identical to the one provided in the cooperative case. Solving the differential equation (20), gives

$$\theta_i^N = -\frac{\varphi_i}{\delta}\left(1 - e^{-\delta(T-t)}\right), \ \theta_i(T) = 0 \tag{26}$$

Inserting in (23) leads to the following equilibrium emission strategy

$$E_i^N = \frac{\delta}{\varphi_i\left(1 - e^{-\delta(T-t)}\right)}, \quad i = 1,2 \tag{27}$$

The difference between cooperative and noncooperative emission lies in the fact that in the latter case, a player takes into account only his marginal damage cost, while in the former one a player takes into account both players marginal damage costs. Since the φ's are positive, emission levels are lower under cooperation, for all t. So is the pollution stock. Indeed, it is easy to verify that the difference in pollution stocks is given by

$$S^N - S^c = \left(\frac{\varphi_1^2 + \varphi_2^2}{\varphi_1\varphi_2(\varphi_1 + \varphi_2)}\right) e^{\delta(T-t)} Log\left(\frac{1 - e^{-\delta T}}{1 - e^{-\delta(T-t)}}\right) > 0 \tag{28}$$

Denote by W_i^N, the Nash equilibrium outcome of player i.

4 Incentive equilibrium

Assume that the players agree before starting the game that the cooperative outcome is the desired one, that is they wish to achieve a collectively social outcome. In the absence of a binding agreement, each player wishes to be assured that when he implements his cooperative strategy, his neighbor will implement also his. Both players wishes will be automatically fulfilled if the desired cooperative outcome is an equilibrium. If one assumes that each player knows his neighbor's current decision when making his own, one may resort to so-called incentive strategies to achieve the cooperative outcome as an (incentive) equilibrium (see Ehtamo and Hämäläinen (1986, 1989, 1993)). An incentive equilibrium has the property that when player i implements his incentive strategy, the best choice for player j is to implement his own incentive strategy.

Since we have obtained that cooperative and noncooperative investment (and hence abatement capacity) decisions coincide, and hence are not incentive controllable, the incentive issue concerns only the emission levels. Formally, an incentive equilibrium is defined as follows. Let $(E_1^c, E_2^c) \in R_+ \times R_+$ denote the desired (cooperative) emission levels. Denote by $\Psi_1 = \{\psi_1 \mid \psi_1 : R_+ \to R_+\}, \Psi_2 = \{\psi_2 \mid \psi_2 : R_+ \to R_+\}$ the sets of admissible incentive strategies defined below.

Definition 2 ***Definition 3*** *Strategy pair* $\psi_1 \in \Psi_1, \psi_2 \in \Psi_2$ *is an incentive equilibrium at* (E_1^c, E_2^c) *if*

$$\begin{aligned} W_1(E_1^c, E_2^c) &\geq W_1(E_1, \psi_2(E_1)), \quad \forall E_1 \in R_+ && (29)\\ W_2(E_1^c, E_2^c) &\geq W_1(\psi_1(E_2), E_2), \quad \forall E_2 \in R_+ && (30)\\ E_1^c &= \psi_1(E_2^c), \quad E_2^c = \psi_2(E_1^c) && (31) \end{aligned}$$

Admissible incentive strategies are assumed to be linear

$$\psi_1(E_2) = E_1^c + \upsilon_1(t)(E_2 - E_2^c), \qquad \psi_2(E_1) = E_2^c + \upsilon_2(t)(E_1 - E_1^c) \tag{32}$$

To identify an incentive equilibrium, one needs to solve a pair of optimal control problems and then finds the optimal values for $\upsilon_1(t)$ and $\upsilon_2(t)$. The optimal control problem for player 1 is defined as follows:

$$\begin{aligned} &\max_{E_1 \geq 0} W_1 && (33)\\ &\text{subject to (1)-(2)} \\ \text{and } E_2 &= \psi_2(E_1) \end{aligned}$$

The Hamiltonian for this problem is the following

$$\begin{aligned} H^1 &= Log E_1 + \beta_1 K_1 - \frac{1}{2} c_1 I_1^2 - \varphi_1 S + \lambda_1 (I_1 - \mu_1 K_1) && (34)\\ &+\theta_1 \left(E_1 + E_2^c + \upsilon_2(t)(E_1 - E_1^c) - \delta S\right) \end{aligned}$$

Optimality conditions for emission and adjoint multiplier for pollution stock are as follows (all others are the same as before and we omit printing them)

$$\dot{\theta}_1 = \delta\theta_1 + \varphi_1, \quad \theta_1(T) = 0 \tag{35}$$
$$E_1 = -\frac{1}{\theta_1(1 + \upsilon_2(t))} \tag{36}$$

Identify the incentive strategy by the superscript I. Solving for θ_1 and substituting in the above equation leads to the incentive emission strategy for player 1

$$E_1^I = \frac{\delta}{\varphi_1(1 + \nu_2(t))\left(1 - e^{-\delta(T-t)}\right)} \tag{37}$$

Following a similar approach for player 2, leads to the following incentive emission strategy

$$E_2^I = \frac{\delta}{\varphi_2(1 + \nu_1(t))\left(1 - e^{-\delta(T-t)}\right)} \tag{38}$$

To determine the values for $\upsilon_1(t)$ and $\upsilon_2(t)$, it suffices to let $E_i^I = E_i^c, i = 1, 2$. It is easy to verify that

$$\upsilon_1(t) = \upsilon_1 = \frac{\varphi_1}{\varphi_2}, \quad \upsilon_2(t) = \upsilon_2 = \frac{\varphi_2}{\varphi_1} \tag{39}$$

Notice that these values are positive and constant over time and that $\upsilon_i = \upsilon_j^{-1}$.

5 Welfare allocation over time

We have yet obtained the optimal joint welfare $W^c (= W_1^c + W_2^c)$. Although it is obvious by virtue of joint maximization that $W^c = W_1^c + W_2^c > W^N = W_1^N + W_2^N$, nothing insures that each player is better off under cooperation. One requirement for cooperation to take place is that the agreement satisfies a global individual rationality condition. To achieve this, one can adopt the egalitarian principle (see, e.g. Moulin (1988)) which gives an equal division of the surplus of cooperation. To achieve this, one defines a total side payment SP such that

$$SP = \frac{1}{2}\left(W_1^c - W_2^c + W_2^N - W_1^N\right) \tag{40}$$

After this side payment has been made, the countries will end up with the following net welfares

$$NW_1 = W_1^c - SP = W_1^N + \frac{W^c - \left(W_1^N + W_2^N\right)}{2} \tag{41}$$
$$NW_2 = W_2^c + SP = W_2^N + \frac{W^c - \left(W_1^N + W_2^N\right)}{2} \tag{42}$$

Obviously each player gets a higher total payoff under cooperation (after side payment) than under a noncooperative regime. Recall that each player objective functional was defined as

$$W_i = \int_0^T \left(LogE_i + \beta_i K_i - \frac{1}{2} c_i I_i^2 - \varphi_i S \right) dt \tag{43}$$

Since for each player the investment cost and abatement capacities are equal under cooperation and noncooperation, the side payment becomes

$$\begin{aligned} SP &= \frac{1}{2}\int_0^T [LogE_1^c - \varphi_1 S^c - LogE_2^c + \varphi_2 S^c \\ &\quad + LogE_2^N - \varphi_2 S^N - LogE_1^N + \varphi_1 S^N] dt \end{aligned} \tag{44}$$

which reduces, after substitution for the E's from (16) and (27), to

$$SP = \frac{1}{2}\int_0^T \left(Log\frac{\varphi_1}{\varphi_2} + (\varphi_1 - \varphi_2)(S^N - S^c) \right) dt \tag{45}$$

Since the pollution stock is higher under noncooperation than under cooperation for all t, it is easy to see that the total side payment is positive if $\varphi_1 > \varphi_2$ and negative if $\varphi_1 < \varphi_2$. If both players marginal damage costs were equal then the side payment would be zero and the cooperative game would be inessential, i.e. there is no incentive for cooperation since there is no surplus of cooperation.

After side-payments have been made, the total welfares are

$$\begin{aligned} NW_1 &= \int_0^T [LogE_1^c + \beta_1 K_1 - \frac{c_1}{2} I_1^2 \\ &\quad - \frac{\varphi_1}{2}(S^N + S^c) + \frac{\varphi_2}{2}(S^N - S^c)] dt \end{aligned} \tag{46}$$

$$\begin{aligned} NW_2 &= \int_0^T [LogE_2^c + \beta_2 K_2 - \frac{c_2}{2} I_2^2 \\ &\quad - \frac{\varphi 2}{2}(S^N + S^c) + \frac{\varphi_1}{2}(S^N - S^c)] dt \end{aligned} \tag{47}$$

Of course, $NW_1 + NW_2 = W^c$, and $NW_i \geq W_i^N$.

We now provide a decomposition over time of these net welfares such that instantaneous dynamic individual rationality is assured. This means that the net instantaneous welfare obtained by each player dominates his net instantaneous non cooperative welfare. The following allocation over time guarantees this requirement

$$\omega_i(t) = \frac{1}{T}\left(NW_i - W_i^N \right) + W_i^N(t) \tag{48}$$

where $W_i^N(t)$ is the instantaneous welfare under non cooperation, that is

$$W_i^N(t) = LogE_i^N + \beta_i K_i^N - \frac{1}{2} c_i \left(I_i^N \right)^2 - \varphi_i S^N \tag{49}$$

and $\omega_i(t)$ is the instantaneous amount allocated to player i.

To be admissible, this allocation must satisfy

$$\int_0^T \omega_i(t)dt = NW_i \tag{50}$$

which is very easy to verify. Further, to satisfy the instantaneous dynamic individual rationality, we must have

$$\omega_i(t) \geq W_i^N(t), \quad \forall t \tag{51}$$

which is obvious since $\frac{1}{T}\left(NW_i - W_i^N\right) \geq 0$.

The economic interpretation of this allocation mechanism is straightforward. Indeed, it recommends to allocate at each instant of time to player i his instantaneous equilibrium welfare plus the average of his dividend of cooperation defined as the difference between his total net cooperative welfare (that is after side payment) and his total non cooperative welfare.

6 Conclusion

To conclude, we would like to stress some of the results obtained and the limits of our approach. Although we have adopted a simple ecological economics model, still the model captures one of the main ingredients of the debate regarding pollution reduction, namely that emissions by one player damages the environment of all. The fact that we needed to resort to simple special functional forms is clearly a drawback. However, it is worth noticing that this has been done for the only purpose of illustrating the construction of an incentive equilibrium. All other results would remain unaltered, including the instantaneous dynamic rationality one, if we had refrained from resorting to functional forms. Finally, it is clearly of interest to investigate the impact of discounting on the results, especially if the game to be considered were of infinite horizon.

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