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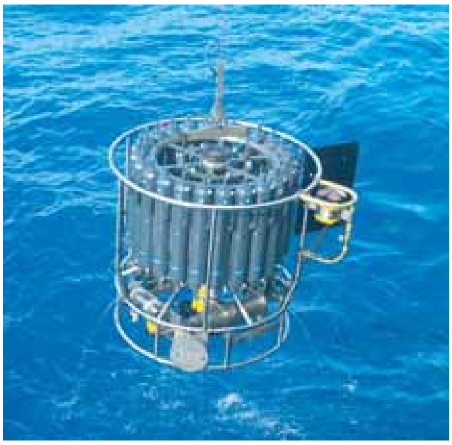
International Max Planck Research School
on Earth System Modelling

Stability and Burden Sharing Emissions in International Environmental Agreements

A Game-Theoretic Approach

Dritan Osmani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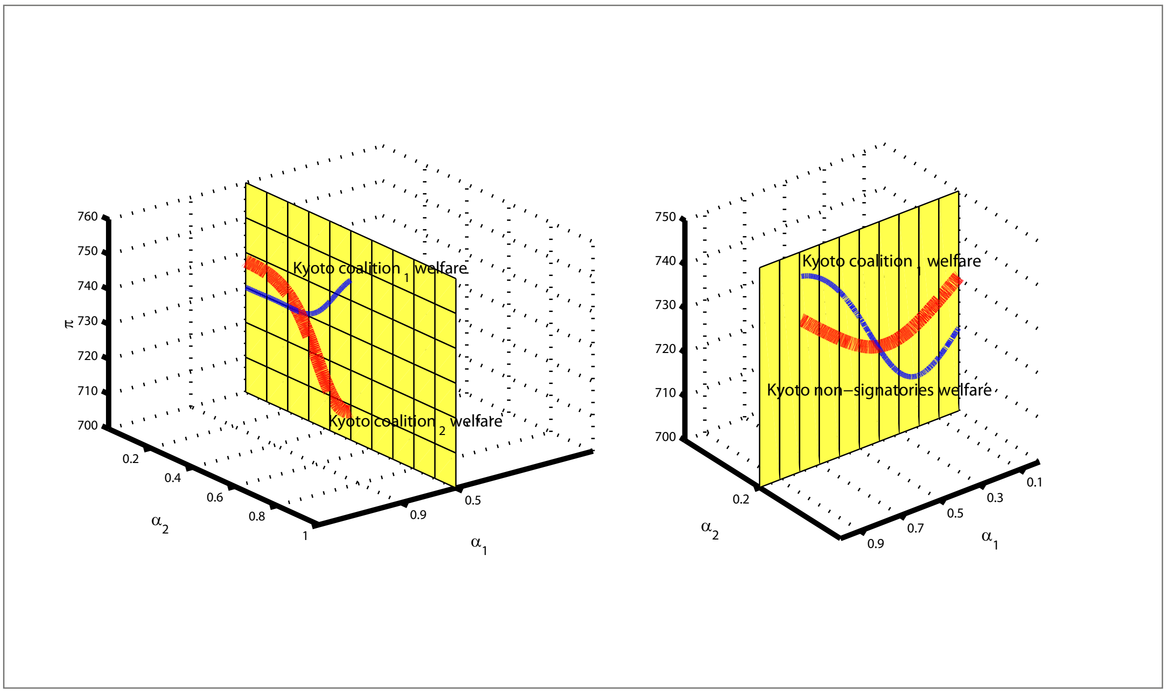

Dritan Osmani

Hamburg 2009

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Outline of Thesis

The body of literature on International Environmental Agreements (IEA) has two conflicting views. One is based on cooperative game theory and concludes that the grand coalition is stable, by assuming transferable utility, then using the γ-core concept and implementing transfers to solve the heterogeneity of the countries involved (Chander & Tulkens 1997, 2006, Eyckmans & Tulkens 2003, Chander 2007). This represents an optimistic view of the possibility of international cooperation on solving global environmental problems. The other view is rooted in the non-cooperative game theory and became the dominant path in the literature (Barrett 1994, 2003, Botteon & Carraro 2001, Osmani & Tol 2005, Finus.etal 2006, Rubio & Ulph 2006, McGinty 2007). The usual approach of non-cooperative game theory to stable IEAs is based on the idea developed for cartel stability (d'Aspremont et al. (1983)) and requires so-called internal and external stability. Internal stability means that a country does not have an incentive to leave the coalition, while external stability means that a country does not have an incentive to join the coalition. This part of the literature reaches the conclusion that the size of a stable coalition is typically very small, thus representing a pessimistic view of global environmental goods[1].
Papers from one to five perform a game theoretic approach, while paper six use welfare analysis.
Firstly, in our game theoretic approach, a link between the economic activity and the physical environment is established which is generated from the integrated assessment model (except first paper which uses stylized social welfare functions). The social welfare function captures the difference between the profit from pollution and the environmental damage. Following this approach, players (countries) play a two stage-game. In the first stage, each country decides whether to join the coalition and become a signatory (or coalition member) or stay singleton and non-signatory (*membership game*). In the second stage, every country decides on emissions (*strategic game*). Within the coalition, players play cooperatively (by maximizing their joint welfare) while the coalition and single countries compete in a non cooperative way (by maximizing their own welfare).

In first paper we use non-cooperative game theory in order to develop further a model from Barrett (1994a). The main assumptions of the model are:

- all countries are identical,
- each country's net benefit function is known and known to be known etc. by all countries
- pollution abatement is the only policy instrument,
- costs are independent of one another.

Being aware of the work on coalition theory by Ray and Vohra (1994), Yi and Shin (1995) and Bloch (1996, 1997) we think that modelling two self-enforcing IEA (employing the stability concept of d'Aspremont et al. (1983)) can bring a better understanding of improving capacity of IEA's. We are less concerned with developing a general theory of coalition formation. Rather, we present and apply a method for computing the maximum size of two coalition. The loss in generality is compensated by a gain in practically. The main contribution of this paper is the discussion on the *possibility of improving capability* (size and emission reduction) of two self-enforcing IEA compared to one self-enforcing IEA by modelling the IEA as a one-shot game. Another contribution is *a different formulation (as nonlinear optimization problem)* of finding α (αN = the number of signatories) in extended Barrett's model. Although our work is less general than that of Yi and Shin, Bloch etc. we are actually able to compute the coalition sizes and optimal abatement levels. We would like to stress that we reinforce the conclusions of Asheim et. al

[1] The references for this paragraph are found in the second paper. Other references can be found in the bibliography of paper which they introduce.

(2006) and Carraro (2000) by following a different method, that is nonlinear optimization. Our first paper considers stylized cost-benefit functions and identical countries which are the main drawbacks of this research. These drawbacks are overcome in the second paper where cost-benefit functions from FUND (developed by Richard Tol) are used, and different world regions are considered (thus not identical).

In the second paper, the IEAs are analyzed by using the farsighted stability concept within the framework of mixed non-cooperative and cooperative game theory. We investigate what outcomes are stable, which implies that they cannot be replaced by any coalition of rational, farsighted and selfish countries. The selfishness of players shapes the aspects of *non-cooperative approach.* The idea of farsightedness means that one should check for multi-step stability by comparing the profits of a coalition member after a series of deviations has come to an end. The deviation is possible only if players (regions) display *cooperate attitude (by forming a coalition)* to each-other in order to increase their welfare.
Farsighted stability developed further the notation of stable sets of von Neumann & Morgenstern (1947). Stable sets are defined to be self-consistent. The notion is characterized by internal and external stability. Internal stability guarantees that the solution set is free from inner contradictions, that is, any two outcomes in the solution set cannot dominate each other and external stability guarantees that every outcome excluded from the solution is accounted for, that is, it is dominated by some outcome inside the solution. Harsanyi (1974) criticizes the von Neumann and Morgenstern solution also for its failing to incorporate foresight. He introduced the concept of indirect dominance to capture foresight. An outcome indirectly dominates another, if there exists a sequence of outcomes starting from the dominated outcome and leading to the dominating one, and at each stage of the sequence the group of players required to enact the inducement prefers the final outcome to its status quo. His criticism inspired a series of works on abstract environments including among others those of Chwe (1994), Mariotti (1997) and Xue (1998). Chwe (1994) introduces the notation of farsighted stability which is applied to the problem of IEAs by Diamantoudi & Sartzetakis (2002) and by Eyckmans (2003). Diamantoudi & Sartzetakis (2002) consider identical countries while asymmetric countries are taken into account in our model. Eyckmans (2003) studies only single farsightedly stable coalitions while we allow multiple farsightedly stable coalitions. In addition, a more systematic way of finding farsightedly stable coalitions is introduced in our approach (as we have 16 different world regions, Eyckmans consider only 5 world regions).
The welfare functions of sixteen world regions are taken from the Climate Framework for Uncertainty, Negotiation and Distribution model FUND (see Section 2.2).
Solving farsighted stability by using combinatorial algorithms, we find all farsightedly stable coalitions. We show that by applying FUND, two farsightedly stable coalitions can be formed. The number of regions in both coalitions is around two thirds of all regions, and they improve welfare and abatement levels significantly. This is one of the few relatively optimistic results of non-cooperative game theory. Another contribution of this paper is the further extension of the farsighted stability concept to preferred farsighted stability. The preferred farsightedly stable coalition is a farsightedly stable coalition where the majority of country members reach higher profits in comparison to any other farsightedly stable coalition[2].

The third paper presents a detailed discussion and comparison of D'Aspremont stability and farsighted stability. We show that the D'Aspremont stable coalitions are often sub-coalitions of farsightedly stable coalitions. Besides, farsightedly stable coalitions can be frequently the largest size coalition. Moreover, they create always the biggest improvement in environmental and welfare that game theory without side payments can realize. Similarly to preferred farsightedly stable coalitions, we introduce preferred D'Aspremont stable coalitions. All D'Aspremont stable coalitions are found and multiple D'Aspremont coalitions are compared with multiple farsighted ones.

The fourth paper develops further our previous work on farsightedly stable coalitions and preferred farsightedly stable coalitions. In our second paper, we show that multiple preferred farsightedly stable coalitions include two thirds of countries and improve significantly the welfare and environment which are optimistic results. Here we extend the discussion on the issue, which farsightedly stable coalitions are more likely to form in different time horizons and how much improvements they bring to welfare and environment. We raise the question if the farsightedly stable coalitions can be maintained for a long-term period. The improvements in welfare and abatement levels of full non-cooperative behavior (atom structure) and grand coalition are considered also.

[2]We consider only *economic incentives* that a region has to join a coalition for environmental protection. Other factors like commitment to cooperation are not taken into account.

The main contribution of the fifth paper is the discussion on the assumption of *joint welfare maximization.* As the members of coalition *play cooperatively* by maximizing their joint welfare, we compare the joint welfare maximization with classical cooperative game theory value such as Shapley Value, Nash bargaining solution and Consensus Value.

The sixth paper addresses the distributional issue which is the cumbersome point of benefit-cost analysis. As per capita income is lower in poor countries, then willingness-to-pay based estimates of damages in poor countries are lower than in the developed countries even though the impact is identical in human, physical or ecological terms. One way of managing this would be to use a normative approach by introducing weight factors based on the different marginal value of money in the different regions of the world. This would give higher weight to costs in the poor countries. Environmental equity can be understood as assuming a new decision criterium that requires that the value of lost lives (also any environmental goods) in rich and poor countries has to be weighted differently. The normative approach is not realistic as it does not respect the WTP estimates which are the base of economic valuation. However, we would like to experiment in order to test the Kyoto emissions reduction targets requiring that the value of life is identical in poor and rich countries.
There are different views in favor and against of using weight factors. We do not plan to review this discussion. We simply assume that weight factors are considered appropriate from a normative point of view, and then examine if the Kyoto emissions reduction targets are consistent with the requirement of valuing the life in poor and developed countries by weighting them differently.
Following Ray (1984) and Stenman (2000) we obtain the equity weights by totally differentiating the social welfare function. The social welfare function depends on three parameters, which are the incomes per capita, the elasticity of marginal utility e and the inequality aversion parameter γ. The incomes per capita depend on GDP, population and costs and benefits from pollution abatement which are obtained from two different integrated assessment models namely the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model developed by Richard Tol, and the MITs Emissions Prediction and Policy Analysis (EPPA) model developed at MIT. The essential point of our paper is the development of a relation between e and γ by equalizing the value of life in poor and rich regions following Fankhauser et al. (1997) and Stenman (2000), but allowing for larger range of parameters values that relates e and γ. As e and γ take their values in specific intervals, there is a significant advantage to have a relation between them, as it is possible to restrict the intervals for e and γ when the world regions are approximated in only two types, namely poor and rich. That is, when the world social welfare for different e and γ is maximized and pollution abatements levels are found, one focuses on smaller intervals for e and γ which are going to give smaller variation for abatement levels. Finally it is possible to test if the abatement targets of Kyoto protocol respect the condition that the value of life is identical in poor and rich countries when equity weights are used. The costs and benefits from pollution abatements are calculated for the year 2010, which is considered as the representative year of the first commitment period of Kyoto protocol that includes the years 2008 through 2012.

Papers are introduced consecutively, first paper first chapter, second paper second chapter and so on. The last chapter provides the conclusions.

Chapter 1

The Case of two Self-Enforcing International Agreements for Environmental Protection

The Case of two Self-Enforcing International Agreements for Environmental Protection

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Abstract

Non-cooperative game theoretical models of self-enforcing international environmental agreements (IEAs) that employ the cartel stability concept of d'Aspremont et al. (1983) frequently use the assumption that countries can sign a single agreement only. We modify the assumption by considering two self-enforcing IEAs. Extending a model of Barrett (1994a) on a single self-enforcing IEA, we demonstrate that there are many similarities between one and two self-enforcing IEAs. But in the case of few countries and high environmental damage we show that two self-enforcing IEA work far better than one self-enforcing IEA in terms of both welfare and environmental equality

Keywords: self-enforcing international environmental agreements, non-cooperative game theory, stability, nonlinear optimization.

JEL: C61, C72, H41

1.1 Introduction

The formation and implementation of International Environmental Agreements (IEA) is the topic of a broad economic literature. A significant part of the literature uses game theory as a tool to understand the formation mechanism of IEAs. There are two main directions of literature on IEAs (for a review of current literature see Finus 2003; Carraro/Siniscalco 1998; Ioannidis/Papandreou/Sartzetakis 2000; Carraro/Eyckmans/Finus 2005). The first direction utilizes the concepts of cooperative game theory in order to model the formation of IEAs. This is a rather optimistic view and it shows that an IEA signed by all countries is stable provided that utility is transferable and side payments are adequate (Chander/Tulkens 1995, 1997). The second direction uses the concepts of non-cooperative game theory to model the formation of IEAs. At the first level, the link between the economic activity and the physical environment is established in order to generate the economical-ecological model. This link is established through a social welfare function. The social welfare function captures the difference between the profit from pollution and the environmental damage. Following this approach, countries play a two stage-game. In the first stage, each country decides to join or not the IEA. In the second stage, every country decides on emissions. The main body of literature examining the formation of IEA within a two stage framework uses a certain set of assumptions. We mention below only the essential ones:

- Decisions are simultaneous in both stages.

- Countries are presented with single agreements.
- When defecting from coalition, a country assumes that all other countries remain in the coalition (this is a consequence of the employed stability concept of d'Aspremont et al (1983) that allows only singleton movements and myopia).
- Within the coalition, players play cooperatively while the coalition and single countries compete in a non cooperative way.

Non-cooperative game theory draws a pessimistic picture of the prospect of successful cooperation between countries. It claims that a large coalition of signatories is hardly stable, and that the free-rider incentive is strong. The model explains the problems of international cooperation in the attendance of environmental spillovers, but cannot explain IEAs with high membership such as the Montreal Protocol. This calls for a modification of the standard assumptions. We mention in the following paragraphs some of the possible modifications.

Maybe the most important development is the work on coalition theory of Ray and Vohra (1994), Yi and Shin (1995) Yi (1997) and Bloch (1995, 1996, 1997). They allow many coalitions to be formed, although they employ different rule of forming coalitions. Ray and Vohra (1994) analyse Equilibrium Binding Agreements (a game in which coalitions can only break up into smaller coalitions), Bloch (1996) shows that the infinite-horizon Coalitional Unanimity game (game in which a coalition is formed if and only if all members agree to form it) yields a unique subgame perfect equilibrium coalition structure. Yi and Shin (1995) examine an Open Membership Coalitional game (in which nonmembers can join a coalition without the permission of existing members). Yi (1997) shows that in the Open Membership Coalitional game the grand coalition can be an equilibrium outcome for *positive externalities*. But for *positive externalities* in the Coalitional Unanimity game, the grand coalition will be rarely an equilibrium. He shows also that for the same game, the grand coalition can rarely be an equilibrium outcome for *negative externalities* due to free-rider problems.

A sequential choice of emission levels means there is a Stackelberg leader (a coalition of signatories), who takes into account the optimal choice of non-signatories that behave as Stackelberg followers (Barrett 1994a and 1997a). Participants have an advantage towards non-participants as they chose the emissions level based on the reaction functions of non-participants.

Ecchia/Mariotti (1998) distinguish two problems in the standard model of self-enforcing IEA. In the basic model, countries are presumed to behave myopically by disregarding other countries' reaction when they make their choices. They modify this assumption by introducing the notion of *farsightedness*. If countries are farsighted, that is they can foresee other countries' reaction to their choices and incorporate them into their decisions, a new notion of stability has to be established. The authors demonstrate that if the idea of farsightedness is placed into the model, the likelihood of larger coalition increases.

Considering asymmetric countries, *transfers* can help to increase membership and success of IEAs (Botteon/Carraro 1997, Carraro/Siniscalco 1993 and Barrett 1997b).

Jeppesen/Andersen (1998) demonstrate that if some countries are committed to cooperation concerning their abatement implies that this group of countries presuppose a leader role in forming the coalition. The leading role allows them to evaluate potential aggregate benefits from increasing the coalition and device side payments to countries that have follower role in order to attain optimum membership.

Hoel/Schneider (1997) integrate *a non-environmental cost function* from not signing the IEA which they call "non-material payoff". They find that, even in the absence of side payments the number of signatories is not very small.

Barrett (1997b) uses a partial equilibrium model to observe the effectiveness of trade sanctions in signing an IEA. He considers only traded goods that are linked to environmental problems. He explains that if the public good agreement is linked to a club agreement, such as a trade agreement, the membership in IEAs can be raised. Botteon/Carraro (1998), Carraro/Siniscalco (1997), Breton/Soubeyran (1998) and Katsoulacos (1997) give similar conclusions.

Carraro/Marchiori/Oreffice (2001) make obvious that the implementation of *a minimum participation clause* can help to improve the success of IEAs. Such a clause implies that a treaty only enters into force if a certain number of signatories have approved it. The minimum participation clauses is fund in almost all IEAs in the past.

Endres (1996 and 1997) shows that the bargaining outcome under the inefficient uniform emission reduction quota regime may have better-quality from an ecological and economic point of view than an efficient uniform tax rate in a two-country model. Endres/Finus (2002) Finus/Rundshagen (1998a), Finus/Rundshagen (1998b) demonstrate that an inefficient emission reduction under the quota regime is rewarded by higher stability and higher membership.

This paper uses non-cooperative game theory in order to develop further a model from Barrett (1994a). Being aware of the recent work on coalition theory by Ray and Vohra (1994), Yi and Shin (1995) and Bloch (1996, 1997) we think that modelling two self-enforcing IEA (employing the stability concept of d'Aspremont et al. (1983)) can bring a better understanding of improving capacity of IEA's. We are less concerned with developing a general theory of coalition formation. Rather, we present and apply a method for computing the maximum size of two coalition. The loss in generality is compensated by a gain in practically. The main contribution of this paper is the discussion on the *possibility of improving capability* (size and emission reduction) of two self-enforcing IEA compared to one self-enforcing IEA by modelling the IEA as a one-shot game. Another contribution is *a different formulation (as nonlinear optimization problem)* of finding α (αN = the number of signatories) in extended Barrett's model. Although our work is less general than that of Yi and Shin, Bloch etc. we are actually able to compute the coalition sizes and optimal abatement levels. We would like to stress that we reinforce the conclusions of Asheim et. al (2006) and Carraro (2000) by following a different method, that is nonlinear optimization.

In section two we describe Barrett's model of one-self enforcing IEA and formulate it differently as a nonlinear optimization problem. In the third section we present our model for two-self enforcing IEA and introduce an essential part of our simulations. In section four we give our conclusions and further suggestions. In the Appendix we present a full description of our simulation.

1.2 Barrett's model

For an IEA to be *self-enforcing* means that no single nonsignatory has an incentive to join an IEA (*External Stability*) and no single signatory has an incentive to withdraw from the agreements (*Internal Stability*). Furthermore, the coalition *has to be profitable*, that is the coalition members pay-off is greater than their pay-off in Nash equilibrium. The IEA's have to be designed so that they are *self-enforcing* because of nonexistence of a supranational authority that can implement and enforce the agreements. The striking result of Barrett's research is that *a self-enforcing IEA* can be signed by a large number of countries only when the difference between fullcooperative and noncooperative payoffs is small. When this difference is large, *self-enforcing IEA* would be signed only by a small number of countries.

The model makes some important assumptions which are:

- all countries are identical,
- each country's net benefit function is known and known to be known etc. by all countries
- pollution abatement is the only policy instrument,
- abatement levels are instantly and costlessly observable,
- the pollutant does not accumulate in the environment,
- costs are independent of one another.

The abatement benefits function $B_i(Q)$, the abatement cost function $C_i(q_i)$ and the profit function π of country i are defined as:

$$B_i(Q) = b(aQ - Q^2/2)/N \tag{1.1}$$

$$C_i(q_i) = cq_i^2/2 \tag{1.2}$$

$$\pi_i = B_i(Q) - C_i(q_i) \tag{1.3}$$

$a \in R^+$, $b \in R^+$ and $c \in R^+$ parameters,

q_i amount of abatement of country i,

Q global abatement $Q = \sum_{i=1}^N q_i$,

N number of identical countries, each of them emits a pollutant.

The marginal abatement benefit and cost of country i are linear, b is the slope of marginal benefit and c is the slope of marginal cost.

The full cooperative outcome is found by maximizing global net benefits $\Pi = \sum_{i=1}^{N} \pi_i$ with respect to Q. The *fullcooperative abatement levels* are:

$$Q_c = aN/(N+\gamma) \tag{1.4}$$

$$q_c = a/(N+\gamma) \tag{1.5}$$

Q_c global abatement, q_c individual's country abatement, $\gamma = c/b$.

The noncooperative outcome is found by maximizing country net benefits π with respect to q_i. The *noncooperative abatement levels* are:

$$Q_0 = a/(1+\gamma) \tag{1.6}$$

$$q_0 = a/N(1+\gamma) \tag{1.7}$$

Q_0 global abatement, q_0 individual's country abatement.

It is obvious that $Q_c > Q_0$.

1.2.1 One self-enforcing IEA

We have αN countries that sign the IEA (signatories) forming a coalition and $(1-\alpha)N$ countries that do not sign the agreements (nonsignatories). In the first stage the coalition of signatories (C_s) try to maximize their net-benefits, the coalition behaves like Stackelberg leader (Barrett 1994a and 1997a). In the second stage every nonsignatory try to maximize his own benefit (after observing the behavior of signatories), they behave like Stackelberg followers. Modelling C_s as a cooperative game, *the Nash bargaining solution will require that each country undertake the same level of abatement.* This implies that if Q_s is the total abatement of signatories and q_s is the single signatory abatement then $Q_s = \alpha N q_s$. Let Q_n be the total abatement of nonsignatories and q_n be the single nonsignatory abatement. As countries are identical *the Nash equilibrium requires that q_n are identical* thus $Q_n = (1-\alpha)Nq_n$. The reaction function of nonsignatories is given by:

$$Q_n(\alpha, Q_s) = (1-\alpha)(a-Q_s)/(\gamma+1-\alpha) \tag{1.8}$$

In order to find $Q_s(\alpha)$ the following nonlinear optimization problem need to be solved:

$$\max\ \Pi_s(Q_s) \quad s.t \quad (1.8) \tag{1.9}$$

where Π_s is the the total benefit of signatories, π_s is the single benefit of a signatory, $\Pi_s = \sum \pi_s$.

The solution is:

$$Q_s^*(\alpha) = a\alpha^2 N\gamma/[(\gamma+1-\alpha)^2 + \alpha^2 N\gamma] \tag{1.10}$$

By substituting (1.10) into (1.8) it follows that:

$$Q_n^*(\alpha) = a(1-\alpha)(\gamma+1-\alpha)/[(\gamma+1-\alpha)^2 + \alpha^2 N\gamma] \tag{1.11}$$

Let's define the *self-enforcing (SE) IEA*. We recall a concept developed for the analysis of cartels stability by d'Aspremont et al. (1983). We assume that we have αN signatories:

Definition 1.1 *An IEA is self-enforcing if and only if it satisfies the following conditions:*

$$\pi_s(\alpha) \geq \pi_n(\alpha - 1/N) \ \textit{and}\ \pi_n(\alpha) \geq \pi_s(\alpha + 1/N).$$

Table 1.1: Analysis of one self-enforcing IEA for different α

α	q_s	q_n	π_s	π_n	Q	Π
0	-	8.6	-	725.5	85.7	7255.1
0.1	1.4	9.2	732.0	721.5	84.6	7225.8
0.2	3.3	9.7	729.2	718.9	83.9	7209.7
0.3	5.5	9.6	726.9	719.2	84.0	7214.8
0.4	7.8	9.0	725.6	723.2	85.0	7241.5
0.5*	9.7*	7.7*	725.8*	730.0*	87.1*	7279.1*
0.6	10.9	6.2	727.4	737.4	89.7	7313.8
0.7	11.3	4.5	729.9	743.2	92.5	7338.7
0.8	11.1	3.1	732.7	746.9	94.9	7355.0
0.9	10.6	1.9	735.3	748.8	96.9	7366.9
1	9.8	-	737.7	-	98.4	7377.0

If first inequality is satisfied, than no signatory wants to withdraw from the IEA. It will reduce costs, but it will reduce benefits even more. This aspect of stability is known as *Internal Stability.* Similarly no nonsignatory wants to join the IEA. It will raise benefits, but it will rise costs even more. This aspect of stability is known as *External Stability.* For both cases *any movement of any country (joining or withdrawing from IEA) will reduce its profit.*

We introduce an example in order to make this clear. Let $a = 100, b = 1.5, c = 0.25$; and define global net benefits (profits) $\Pi(\alpha) = \alpha N\pi_s + (1-\alpha)N\pi_n$. Table(1.1) shows the net benefit (profit) and abatement levels for representative country i of signatories (C_s) as well as for representative country i of nonsignatories (C_n) for each possible α. It also shows the global net benefits Π and the global abatement level Q. Figure(3.1) gives a graphical relation between the profit of a single country of signatories and nonsignatories and alpha. From Table(1.1) and Figure(3.1) it is clear that the stability conditions are satisfied for $\alpha = 0.5$.

The example indicates how one can find the number of countries that can form a self-enforcing IEA which is αN. A very simple algorithm for finding α (i = number of signatories) can be:

Table 1.2: A simple algorithm for finding α for one self-enforcing IEA

$for \quad i = 1 \quad to \quad N$
$\alpha = i/N$
if $\quad [\pi_s(\alpha) \geq \pi_n(\alpha - 1/N) \wedge \pi_n(\alpha) \geq \pi_s(\alpha + 1/N)]$
save α.

Please note that for our function's specification we have only one α. We introduce a new formulation of our problem. We formulate it *as nonlinear optimization one*, because this formulation can be used to solve the problem of *two self-enforcing IEA*.

$\max \alpha$

$$s.t \quad [\pi_s(\alpha) \geq \pi_n(\alpha - 1/N) \wedge \pi_n(\alpha) \geq \pi_s(\alpha + 1/N)] \tag{1.12}$$

The problem can be formulated as of minimization one[1].

1.3 Two self-enforcing IEA

In the case of two self-enforcing agreements we have two coalition of signatories; the first coalition (C_{s_1}) with $\alpha_1 N$ countries, and the second one (C_{s_2}) with $\alpha_2 N$ countries, and $(1-\alpha_1-\alpha_2)N$ nonsignatories (C_n). Firstly the coalition of signatories (C_{s_1}) (*Stackelberg leader*[2]) and the second coalition of signatories (C_{s_2}) (*first Stackelberg follower*) are formed; they try to maximize their net-benefits ;every coalition knows the

[1] αN usually will not be an integer number, but we round down, then find $\alpha_{new} = rounddown(\alpha N)/N$. Using Matlab Optimization Toolbox, minimization proved to be more robust. In our experience the starting point can be slightly problematic, but as we know that $\alpha \in [0, 1]$ it is easily overcome.

[2] Note that this sequential game can be easily changed by taking as Stackelberg leader C_{s_2}. Or by taking both of C_{s_1} and C_{s_2} as Stackelbergs leaders playing a simultaneous Nash-Cournot equilibrium between each-other.

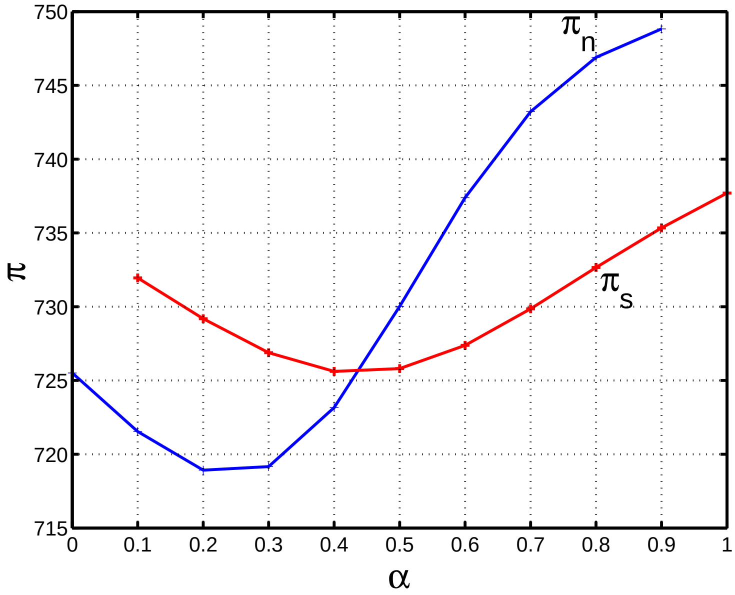

Figure 1.1: Stability analysis of IEA

number of countries in the other coalition. After observing the choice of signatories, every nonsignatory (*second Stackelberg followers*) maximizes its own net benefit by taking the abatement level of signatories coalition and other nonsignatories as given. Let Q_{s_1} be the total abatement of C_{s_1}, q_{s_1} be the single signatory abatement of C_{s_1}; let Q_{s_2} be the total abatement of C_{s_2}, q_{s_2} be the single signatory abatement of C_{s_2}; let Q_n be the total abatement of C_n, q_n be the single signatory abatement of C_n. The same arguments as before imply that $Q_{s_1} = \alpha_1 q_{s_1} N$, $Q_{s_2} = \alpha_2 q_{s_2} N$, $Q_n = (1 - \alpha_1 - \alpha_2) q_n N$.

Let's summarize the notation that we use in this section:

$\alpha \quad = \alpha_1 + \alpha_2,$

$Q = Q_s + Q_n,$

Q : total abatement level,

Q_s: total abatement level of two coalition of signatories,

Q_n: total abatement level of nonsignatories,

$Q_s = Q_{s_1} + Q_{s_2},$

Q_{s_1}: total abatement level of first coalition,

Q_{s_2}: total abatement level of second coalition,

π_{s_1} : the profit of a country of first coalition of signatories,

$\Pi_{s_1} = \sum_1^{\alpha_1 N} \pi_i = \alpha_1 N \pi_{s_1}$ the total profit of first coalition of signatories,

q_{s_1}: the abatement level of a country of first coalition of signatories,

π_{s_2}: the profit of a country of first coalition of signatories,

$\Pi_{s_2} = \sum_1^{\alpha_2 N} \pi_i = \alpha_2 N \pi_{s_2}$ the total profit of second coalition of signatories,

q_{s_2}: the abatement level of a country of first coalition of signatories,

π_n: the profit of a country of nonsignatories,

q_n: the abatement level of a country of nonsignatories.

The profit function of country i for the first, the second coalition of signatories and for nonsignatories is given by:

$$\pi_{s_1} = b(aQ - Q^2/2)/N - cq_{s_1}^2/2$$

$\pi_{s_2} = b(aQ - Q^2/2)/N - cq_{s_2}^2/2$

$\pi_n = b(aQ - Q^2/2)/N - cq_n^2/2$

The reaction function of nonsignatories is similarly found by maximizing the profit of a single nonsignatory π_n:

$$Q_n(\alpha_1, \alpha_2, Q_{s_1}, Q_{s_2}) = (1-\alpha)(a - Q_s)/(\gamma + 1 - \alpha) \tag{1.13}$$

Note that above we have $Q_n = f(\alpha_1, \alpha_2, Q_{s_1}, Q_{s_2})$, so the Q_n is not independent variable anymore. In order to find $Q_{s_2} = f(\alpha_1, \alpha_2, Q_{s_1})$, we need to solve the following optimization problem:

$$\max \Pi_{s_2}(Q_{s_2}) \quad s.t \quad (5.4) \tag{1.14}$$

As $\Pi_{s_2} = b(aQ - Q^2/2) - cQ_{s_2}^2/(2\alpha_2 N)$, the above optimization problem can be transformed to a nonconstrained one by replacing the equation (5.4) to objective function Π_{s_2}. As $d^2\Pi_{s_2}/dQ_{s_2}^2 < 0$ then by $d\Pi_{s_2}/dQ_{s_2} = 0 \Rightarrow Q_{s_2} = f(\alpha_1, \alpha_2, Q_{s_1})$. We do not write explicitly $Q_{s_2} = f(\alpha_1, \alpha_2, Q_{s_1})$ because of the lengthy analytical formula, but note that Q_{s_2} is expressed by means of other variables. In order to find $Q_{s_1} = f(\alpha_1, \alpha_2)$, we need to solve the similar optimization problem:

$$\max \Pi_{s_1}(Q_{s_1})$$

$$s.t \quad Q_n(\alpha_1, \alpha_2, Q_{s_1}) = (1-\alpha)(a - Q_s)/(\gamma + 1 - \alpha), \quad Q_{s_2} = f(Q_{s_1}) \tag{1.15}$$

As $\Pi_{s_1} = b(aQ - Q^2/2) - cQ_{s_1}^2/(2\alpha_1 N)$ than the above optimization problem can be transformed to a nonconstrained one by replacing the constrains to objective function Π_{s_1}. As $d^2\Pi_{s_1}/dQ_{s_1}^2 < 0$ then by $d\Pi_{s_1}/dQ_{s_1} = 0 \Rightarrow Q_{s_1} = f_{s_1}(\alpha_1, \alpha_2)$. As we have $Q_{s_1} = f_{s_1}(\alpha_1, \alpha_2)$, we replace it in $Q_{s_2} = f(Q_{s_1}, \alpha_1, \alpha_2)$ and have $Q_{s_2} = f_{s_2}(\alpha_1, \alpha_2)$. We replace both of them in (5.4) then we get $Q_n = f_n(\alpha_1, \alpha_2)$. Finally we have all $\pi_{s_2}, \Pi_{s_2}, \pi_{s_1}, \Pi_{s_1}, \pi_n, \Pi_n$ as $f(\alpha_1, \alpha_2)$.

In order to find α_1 and α_2 we need to formulate a different optimization problem. We need the conditions of one self-enforcing agreements to be satisfied between three groups of countries, the coalition one of signatories, (C_{s_1}), the coalition two of signatories, (C_{s_2}) and the nonsignatories, (C_n) in order to have *intercoalition stability.* ***The intercoalition stability*** means a stable relations between C_{s_2} and C_n, C_{s_1} and C_{s_2} as well as C_{s_1} and C_{s_2}.

Definition 1.2 We have **intercoalition stability** if and only if the following conditions (1.16),(1.17) and (1.18) are satisfied:

$$[\pi_{s_1}(\alpha_1, \alpha_2) \geq \pi_n(\alpha_1 - 1/N, \alpha_2) \wedge \pi_n(\alpha_1, \alpha_2) \geq \pi_{s_1}(\alpha_1 + 1/N, \alpha_2)] \tag{1.16}$$

$$[\pi_{s_2}(\alpha_1, \alpha_2) \geq \pi_n(\alpha_1, \alpha_2 - 1/N) \wedge \pi_n(\alpha_1, \alpha_2) \geq \pi_{s_1}(\alpha_1, \alpha_2 + 1/N)] \tag{1.17}$$

$$[\pi_{s_2}(\alpha_1, \alpha_2) \geq \pi_{s_1}(\alpha_1 + 1/N, \alpha_2 - 1/N) \wedge \pi_{s_1}(\alpha_1, \alpha_2) \geq \pi_{s_2}(\alpha_1 - 1/N, \alpha_2 + 1/N)] \tag{1.18}$$

It is important to note that *conditions (1.16),(1.17) and (1.18) together describe all possible changes among C_{s_1},C_{s_2} and C_n if only one country is changing its position. It is clear that any change in any country position reduce its profit. In other words they guarantee stability among two coalitions and nonsignatories, so they guarantee* ***intercoalition stability****.*

Now we are ready to formulate the nonlinear optimization problem that helps us to find α_1 and α_2.

$\max\,(\alpha_1 + \alpha_2)$

s.t

$[\pi_{s_1}(\alpha_1, \alpha_2) \geq \pi_n(\alpha_1 - 1/N, \alpha_2) \wedge \pi_n(\alpha_1, \alpha_2) \geq \pi_{s_1}(\alpha_1 + 1/N, \alpha_2)]$

$[\pi_{s_2}(\alpha_1, \alpha_2) \geq \pi_n(\alpha_1, \alpha_2 - 1/N) \wedge \pi_n(\alpha_1, \alpha_2) \geq \pi_{s_1}(\alpha_1, \alpha_2 + 1/N)]$

$[\pi_{s_2}(\alpha_1, \alpha_2) \geq \pi_{s_1}(\alpha_1 + 1/N, \alpha_2 - 1/N) \wedge \pi_{s_1}(\alpha_1, \alpha_2) \geq \pi_{s_2}(\alpha_1 - 1/N, \alpha_2 + 1/N)]$

The constrains of above optimization problem are just the conditions (1.16),(1.17) and (1.18). We use the MATLAB Optimization Toolbox to solve the above optimization problem.

As one would expect the starting point and rounding are cumbersome[3].

Let introduce an example in order to illustrate our results. The parameter values are: $a = 100, b = 1.5, c = 0.25, N = 10$. The solution of our nonlinear optimization problem is, $\alpha_1 = 0.54, \quad \alpha_2 = 0.22$. After we round down, we have $\alpha_1 = 0.5, \quad \alpha_2 = 0.2$, note that after rounding down our constrains (1.16), (1.17) and (1.18) are still satisfied. As $q_{s_1},\ q_{s_2},\ q_n,\ \pi_{s_1},\ \pi_{s_2},\ \pi_n$ are function of only α_1 and α_2 we know all of them. As profit functions depend on α_1 and α_2 we use also a 3-dimensional visualization. Note that we introduce graphics $\alpha \in [0, 1]$, but the α's that we are interested in, satisfy that αN is a natural number.

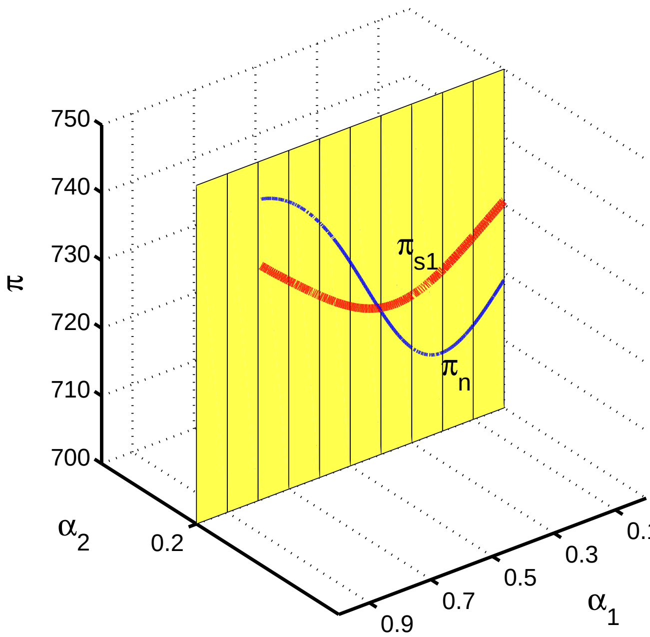

Figure 1.2: Graphical analysis of stability between first coalition and nonsignatories

[3]The starting point is slightly problematic but with the help of algorithm in Table (1.2) we can find a starting point for α_1. As the interval of α_2 is small, it is not difficult to find the second starting point. As with the case of one self-enforcing IEA, $\alpha_1 N$ and $\alpha_2 N$ will usually not be integer numbers, so we only can round both of them down and find the new $\alpha_1^{new} = rounddown(\alpha_1 N)/N$ and $\alpha_2^{new} = rounddown(\alpha_2 N)/N$. After rounding down we check if six constrains are still satisfied (for one self-enforcing IEA there were only two constrains).

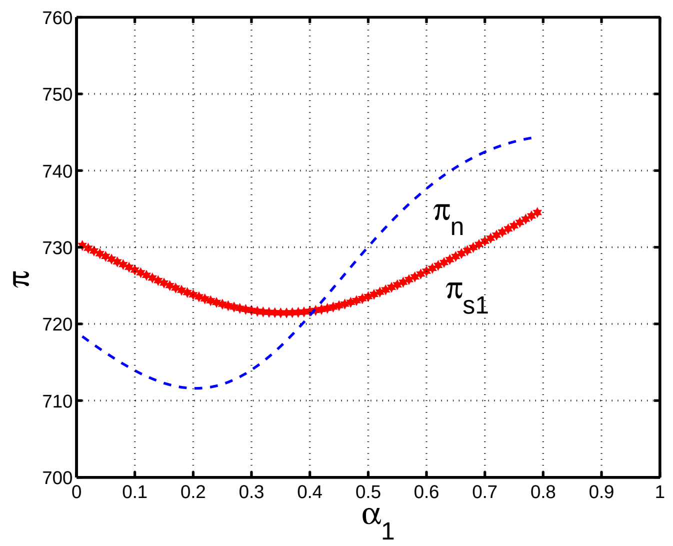

Figure 1.3: Graphical analysis of stability between first coalition and nonsignatories

In Figure (1.2) we introduce graphically the stable relation between π_{s_1}, the profit of a country of first coalition and π_n, the profit of a single nonsignatory (for $\alpha_1 = 0.5$ the relation is stable). In the plane $\alpha_2 = 0.2$ (the size of second coalition is constant) parallel to YZ-plane, the π_{s_1}, π_n are function of only α_1. In Figure (1.3) we see the plane $\alpha_2 = 0.2$ only in 2 dimension. Note that if country changes its position from C_{s_1} to C_n or in the opposite direction he reduces his profit. This means the condition (1.16) is satisfied (any change of $\alpha_1 = 0.5$ with $1/N = 0.1$ reduces π_{s_1} and π_n).

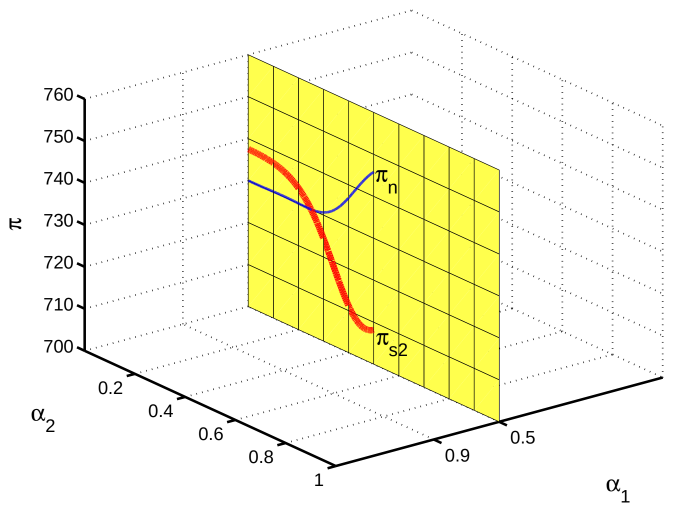

Figure 1.4: Graphical analysis of stability between second coalition and nonsignatories

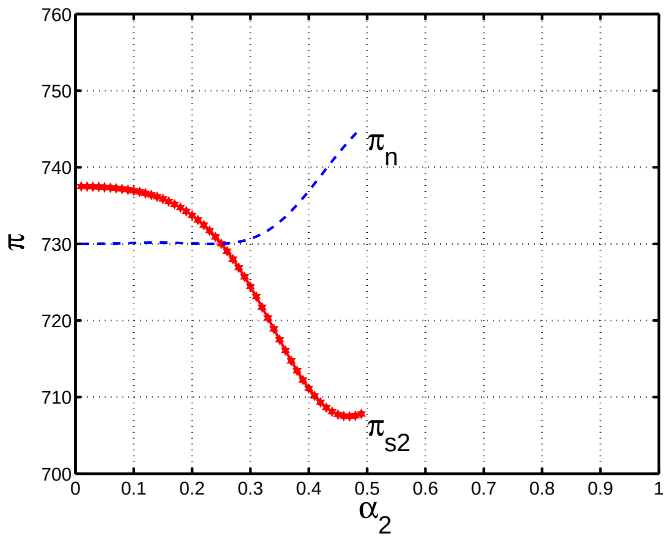

Figure 1.5: Graphical analysis of stability between second coalition and nonsignatories

The Figures (1.4) and (1.5) are similar to Figures (1.2) and (1.3) but we introduce graphically the stable relation between π_{s_2}, the profit of a country of first coalition and π_n, the profit of a single nonsignatory (for $\alpha_2 = 0.2$ the relation is stable). The graphical relation is shown in the plane $\alpha_2 = 0.5$ (the size of first coalition is constant) parallel to XZ-plane. This means the condition (1.16) is satisfied (any change of $\alpha_2 = 0.2$ with $1/N = 0.1$ reduces π_{s_2} and π_n).

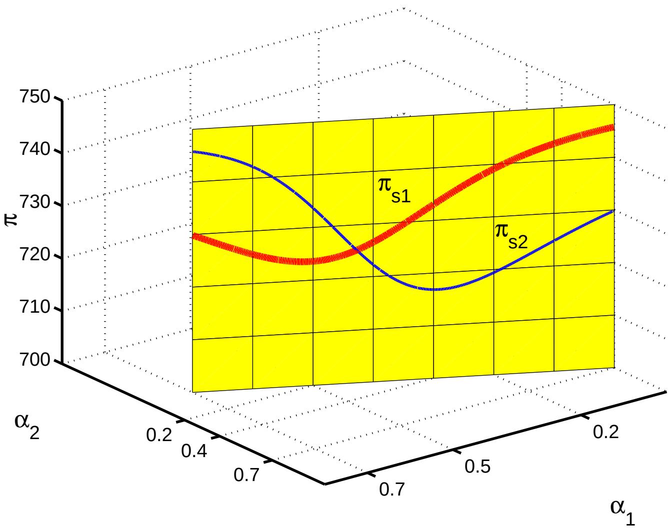

Figure 1.6: Graphical analysis of stability between first and second coalition

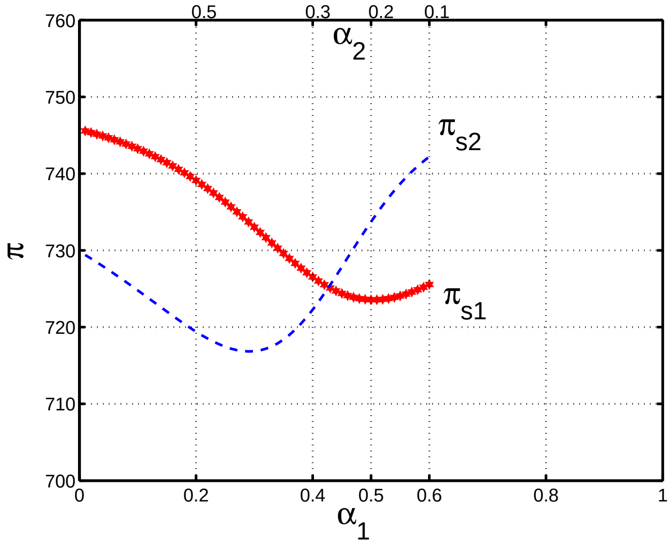

Figure 1.7: Graphical analysis of stability between first and second coalition

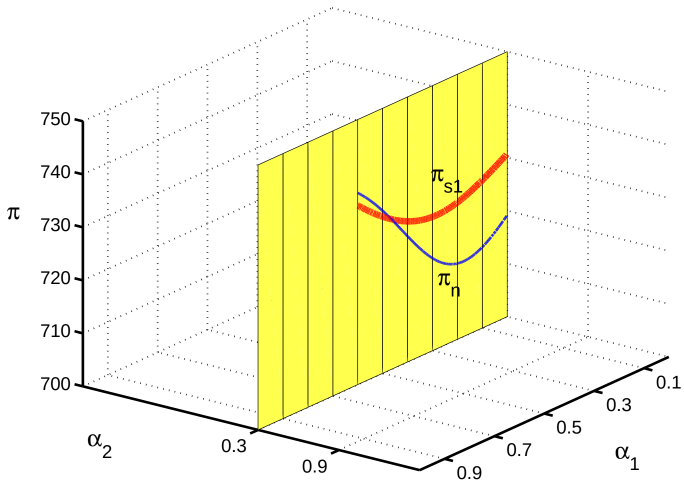

Figure 1.8: Graphical analysis of stability between first coalition and nonsignatories

In Figure (1.6) we present graphically the stable relation between π_{s_1}, the profit of a country of first coalition and π_{s_2}, the profit of a country of second coalition (for $\alpha_1 = 0.5, \alpha_2 = 0.2$ the relation is stable). In the plane $\alpha_1 + \alpha_2 = 0.7$ (the number of nonsignatories is constant) parallel to Z-axes,the π_{s_1}, π_{s_2} are function of only α_1 or α_2(as $\alpha_1 + \alpha_2 = 0.7 = constant$). We chose the plane $\alpha_1 + \alpha_2 = 0.7$ because in this plane is located our solution $\alpha_1 = 0.5, \quad \alpha_2 = 0.2$. In Figure (1.7) we see the plane $\alpha_1 + \alpha_2 = 0.7$ in 2 dimension. In the upper part of the Figure (1.7) we put the values of α_2 too. Note that a country that changes its position from C_{s_1} to C_{s_2} or in the opposite direction reduces his profit (any change of $\alpha_1 = 0.5, \alpha_2 = 0.2$, simultaneously with $1/N = 0.1$ reduces π_{s_1} and π_{s_2}).

It is clear that *all introduced pictures holds simultaneously.*

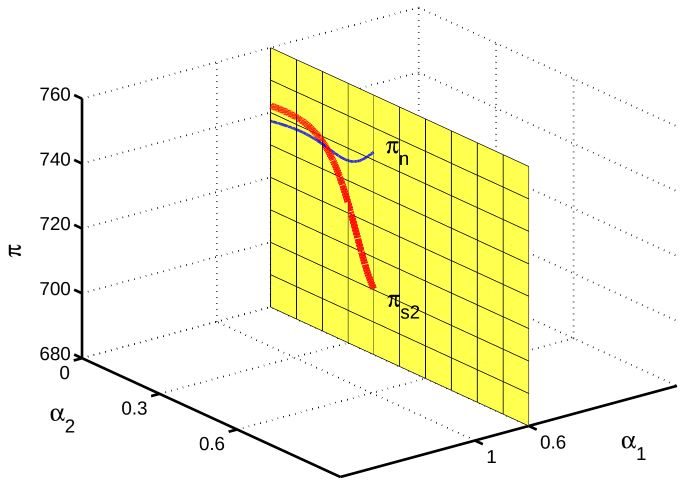

Figure 1.9: Graphical analysis of stability between second coalition and nonsignatories

In Figure (1.8) we introduce again the relation between π_{s_1}, the profit of a country of first coalition and π_n, the profit of a single nonsignatory, but now for $\alpha_2 = 0.3$. The first coalition is still stable, but the Figures (1.4) and (1.5) point out that the second coalition becomes unstable for $\alpha_2 = 0.3$.

In Figure (1.9) we introduce the relation between π_{s_2}, the profit of a country of second coalition and π_n, the profit of a single nonsignatory, but now for $\alpha_1 = 0.6$ (note that for $\alpha_1 = 0.4$ the same result holds). The second coalition is still stable, but the Figures (1.2) and (1.3) point out that the first coalition becomes unstable for $\alpha_1 = 0.6$.

So any change of position of a country (among C_{s_1}, C_{s_2} and C_n) breaks down the *intercoalition stablity*.

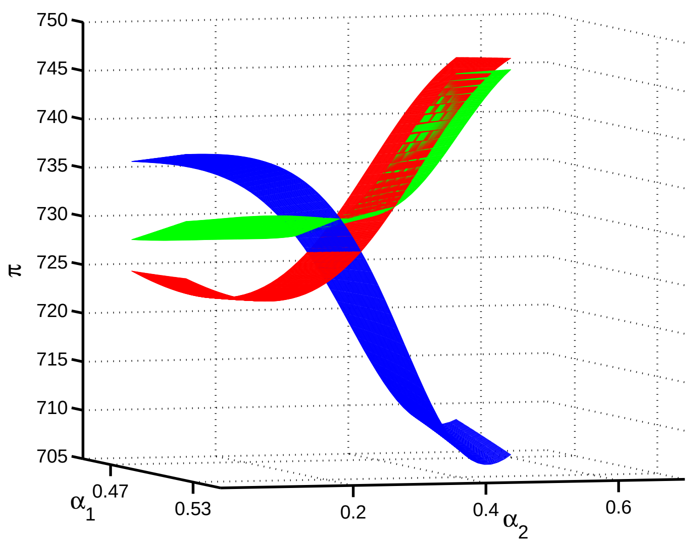

Figure 1.10: Graphical analysis of stability between first coalition, second coalition and nonsignatories. π_{s_1} is red, π_{s_2} is blue and π_n is green.

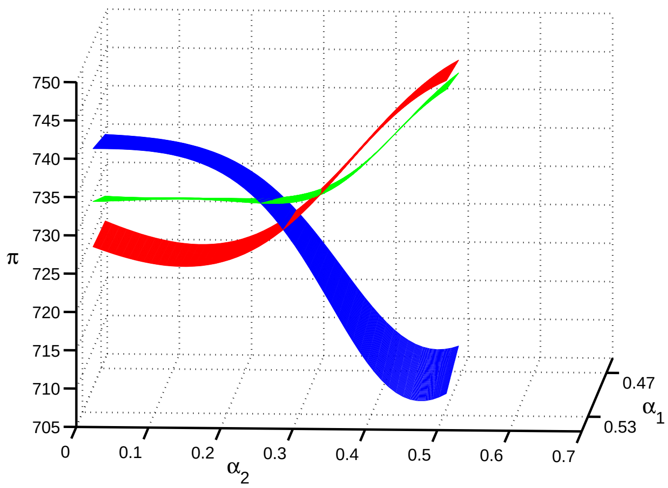

Figure 1.11: Graphical analysis of stability between first coalition, second coalition and nonsignatories. π_{s_1} is red, π_{s_2} is blue and π_n is green.

In Figures (1.10) and (1.11) we just present two 3-dimensional graphs (the same graph form different view) of the relation between π_{s_1}, the profit of a country of first coalition, π_{s_2}, the profit of a country of first coalition and π_n, the profit of a single nonsignatory.

1.3.1 Simulations

We present in this section the essential part of our simulations and we postpone the detailed description of them in Appendix. Firstly let's define:

$\Pi_{\alpha=0} = N\pi_n = \Pi_n$: the global profit, no coalition.
$\Pi_{\alpha=1} = N\pi_s = \Pi_s$: the global profit, grand coalition.
$\Pi_{\alpha_1} = \alpha_1 N\pi_{s_1} + (1-\alpha_1)N\pi_n = \Pi_{s_1} + \Pi_n$: the global profit, one coalition.
$\Pi_{(\alpha_1,\alpha_2)} = \alpha_1 N\pi_{s1} + \alpha_2 N\pi_{s2} + (1-\alpha_1-\alpha_2)N\pi_n = \Pi_{s1} + \Pi_{s2} + \Pi_n$: the global profit, two coalitions.

$Q_{\alpha=0} = Nq_n = Q_n$: the global abatement, no coalition.
$Q_{\alpha=1} = Nq_s = Q_s$: the global abatement, grand coalition.
$Q_{\alpha_1} = \alpha_1 Nq_{s1} + (1-\alpha_1)Nq_n = Q_{s1} + Q_n$: the global abatement, one coalition.
$Q_{(\alpha_1,\alpha_2)} = \alpha_1 Nq_{s1} + \alpha_2 Nq_{s2} + (1-\alpha_1-\alpha_2)Nq_n = Q_{s1} + Q_{s2} + Q_n$: the global abatement, two coalitions.

the fraction of fully cooperative welfare
$(\Pi_{\alpha_1} - \Pi_{\alpha=0})/(\Pi_{\alpha=1} - \Pi_{\alpha=0})$: for one coalition.
$(\Pi_{(\alpha_1,\alpha_2)} - \Pi_{\alpha=0})/(\Pi_{\alpha=1} - \Pi_{\alpha=0})$: for two coalitions.

the fraction of fully cooperative abatement
$(Q_{\alpha_1} - Q_{\alpha=0})/(Q_{\alpha=1} - Q_{\alpha=0})$: for one coalition.
$(Q_{(\alpha_1,\alpha_2)} - Q_{\alpha=0})/(Q_{\alpha=1} - Q_{\alpha=0})$: for two coalitions.

α_1: the fraction of countries in one coalition.
$(\alpha_1 + \alpha_2)$: the fraction of countries in two coalitions.

As we know form simulation that *the important parameters are γ and N* we introduce results by varying these parameters.

The Figures (1.12), (1.13), and (1.14) use the data from Tables (1.3), (1.14) in Appendix. The set of parameters are: a = 100, N = 10 and we vary $\gamma = c/b$. It is clear from that the fraction of fully cooperative welfare, the fraction of fully cooperative abatement and the fraction of countries in two coalition increase if we increase $\gamma = c/b$ for two self-enforcing agreements (two coalition) compared to one self-enforcing agreements (one coalition). When γ *is small*, one coalition is better than two coalitions.

The Figures (1.15), (1.16), and (1.17) use the data form Tables (1.7) and (1.8) in Appendix. The set of parameters are: a = 100, c = 0.25, b = 1.5 so $\gamma = c/b = 0.167$; a = 100, c = 0.3, b = 1.5, $\gamma = c/b = 0.833$; a = 100, c = 150, b = 25, $\gamma = c/b = 6$ and we vary N (total number of countries). From the figures we derive the main conclusion that *if the damage cost is relative big (γ large), and if the number of countries is small* then two coalitions improve the welfare and abatement level significantly compared to one coalition. In all cases a higher N implies less additional welfare and abatement due to the second coalition. So, a second coalition is more effective with a small number of countries than with a large number.

1.4 Conclusions

The paper investigates the size and the improving capability of two self-enforcing IEA. An IEA is self-enforcing when no country wants to withdraw and no country wants to join the IEA. As we employ a simplified model the results must be interpreted with caution. Although our work is less general than that of Yi and Shin, Bloch etc, we are able to compute the coalition sizes and optimal abatement levels.

We find that adding a second coalition improves welfare and environmental quality when the number of players is small and cost of pollution is high. That is, multiple coalitions help with continental environmental problems, but not with global environmental problems. At first sight, this conclusion is counterintuitive. Surely, bigger problems require a larger number of coalitions? However, the intuition behind the result follows from Barrett's (1994) analysis. Barrett (1994) shows that stable coalitions are either small or irrelevant. "He also shows" / "Here we extend that result to show" that the share of players that cooperate grows if the number of players fall.

Consider a serious environmental problem with a large number of players. According to Barrett (1994), only a small coalition would form. If we take the cooperative players out of the population, we are left with a still large number of players with a still serious environmental problem. In this subpopulation, only a small coalition would form. So, a second coalition does not add much. In fact, the additional constraint of inter-coalition stability more than offsets the gains of cooperation in the second coalition.

Now consider a serious environmental problem with a medium number of players. According to Barrett (1994), only a small coalition would form. If we take these players out of the population, we are left with smaller number of players with a considerable environmental problem. In this subpopulation, a larger coalition would form. That is, a second coalition does improve welfare and environmental quality. In this case, the inter-coalition stability constraint reduces but not eliminates these gains.

If this intuition is correct, one may suspect that an environmental problem with a large number of players requires a high number of coalitions – and that only the "last" coalition will contribute to gains in welfare and environmental quality. However, with every additional coalition, the number of inter-coalition stability constraints grows combinatorially. This would offset these gains, and limits the number of coalitions that can form. This problem is deferred to future research.

As always further research is needed in asymmetry between countries, independence cost function, issue linkage, repeated games, uncertainty or limited information.

Acknowledgment

We would like to thank Stefan Napel for his nice comments and suggestions.

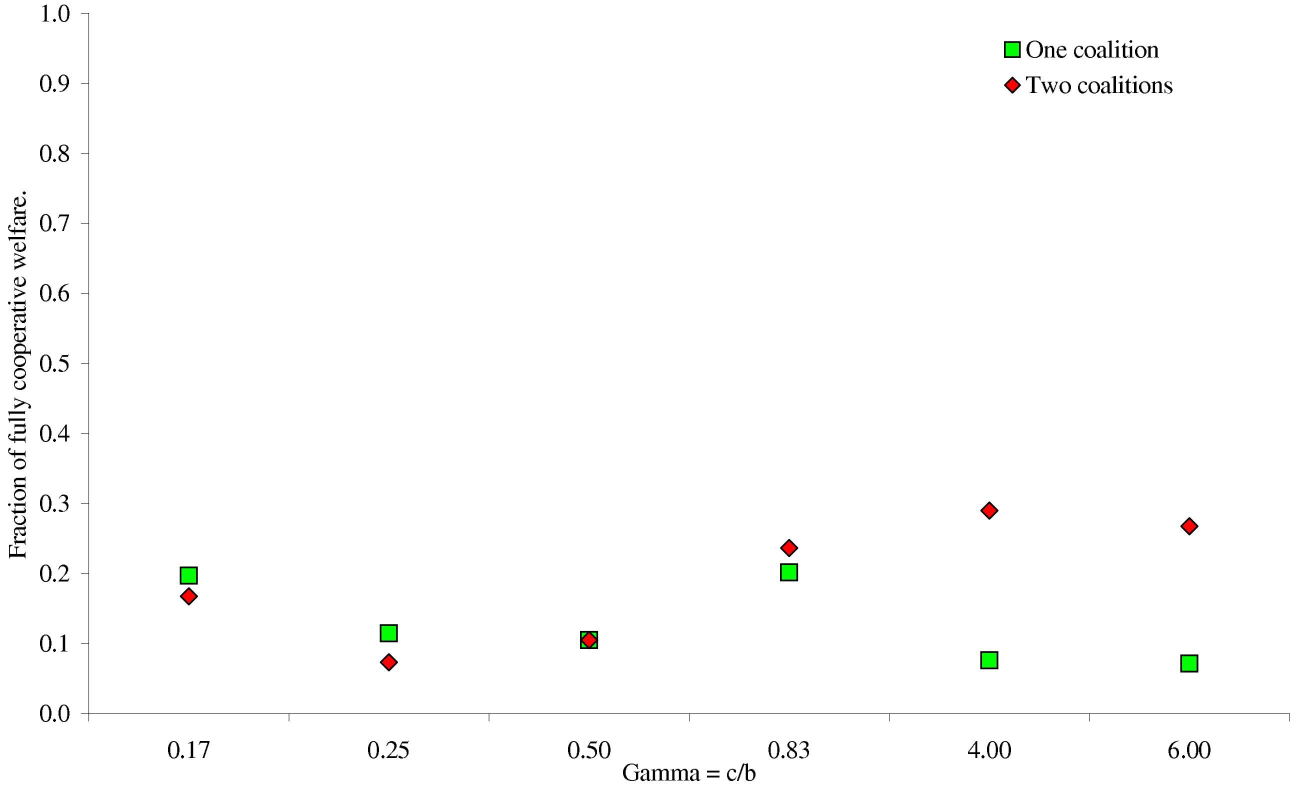

Figure 1.12: Profit Π as function of γ ($= c/b$) for one and two self-enforcing IEA.

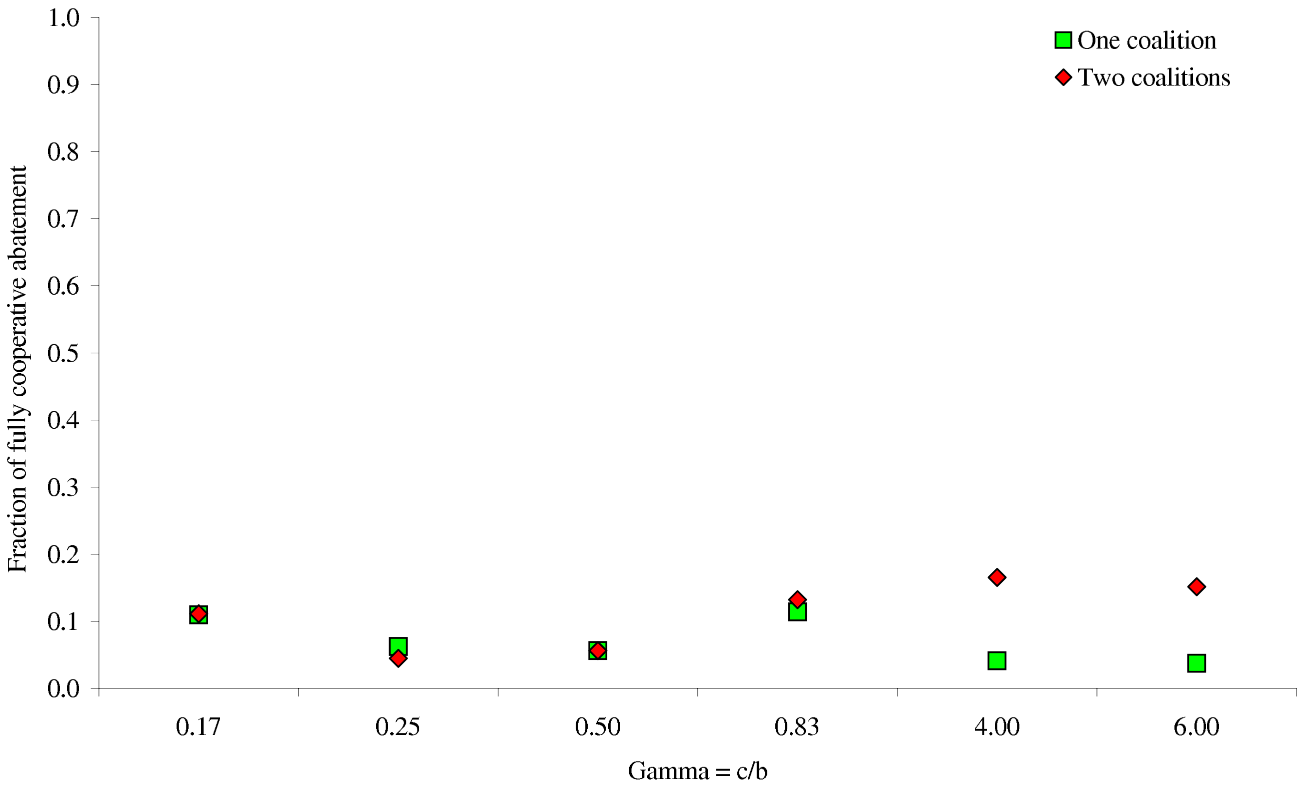

Figure 1.13: Abatement Q as function of γ $(= c/b)$ for one and two self-enforcing IEA.

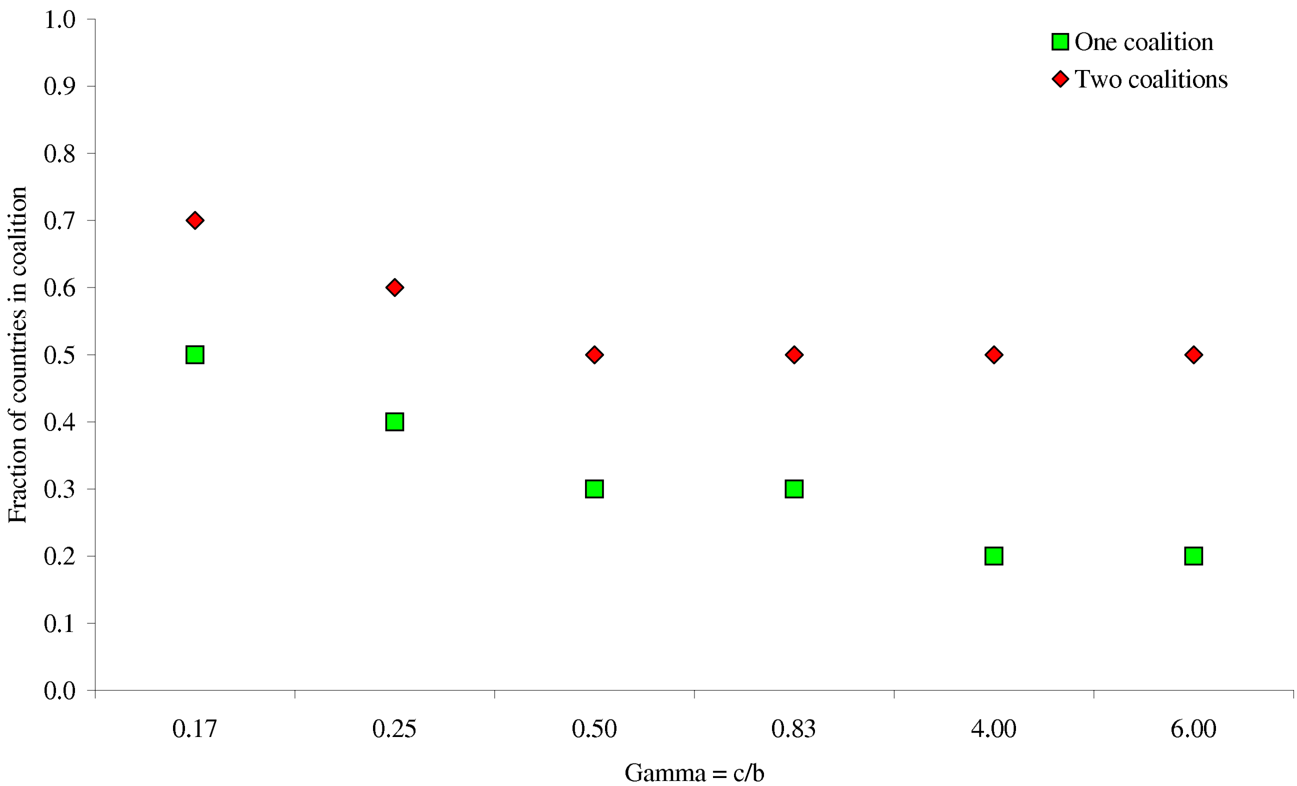

Figure 1.14: Coalition size as function of γ $(= c/b)$ for one and two self-enforcing IEA.

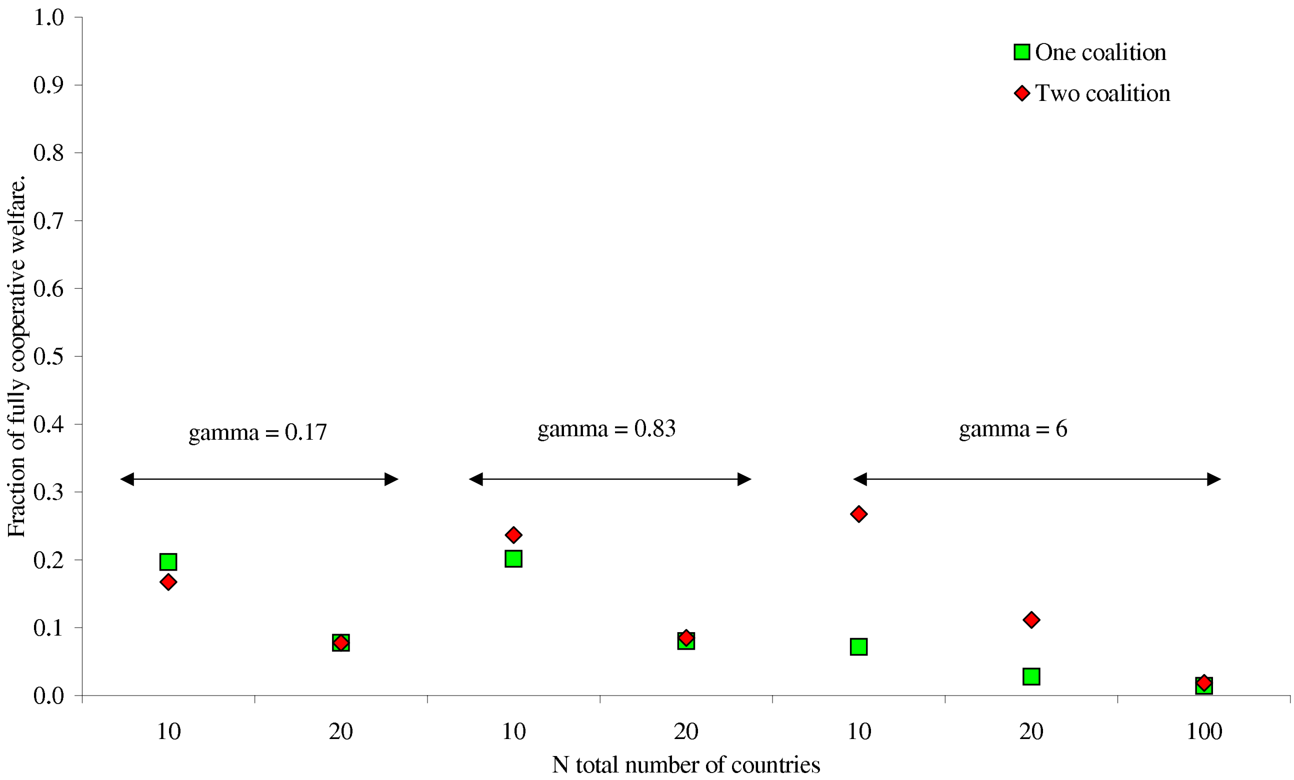

Figure 1.15: Profit Π as function of N and γ for one and two self-enforcing IEA.

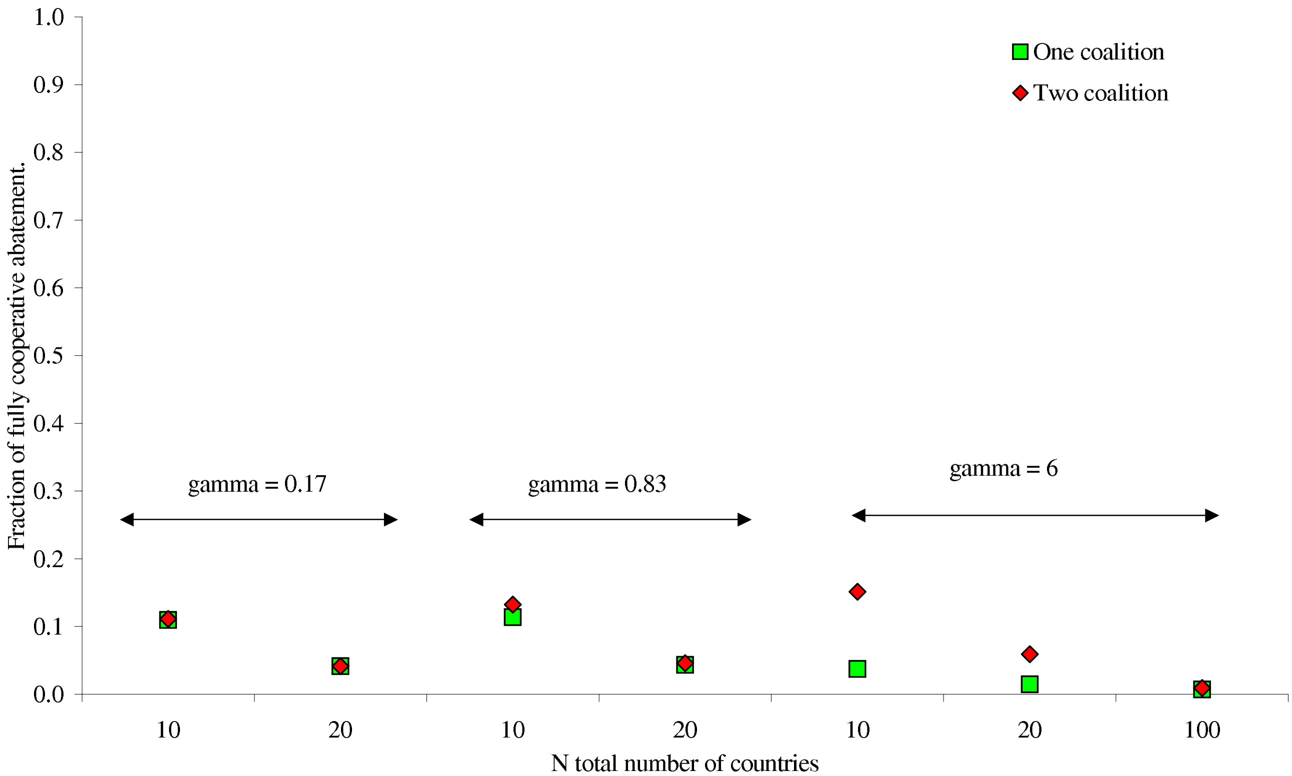

Figure 1.16: Abatement Q as function of N and γ for one and two self-enforcing IEA.

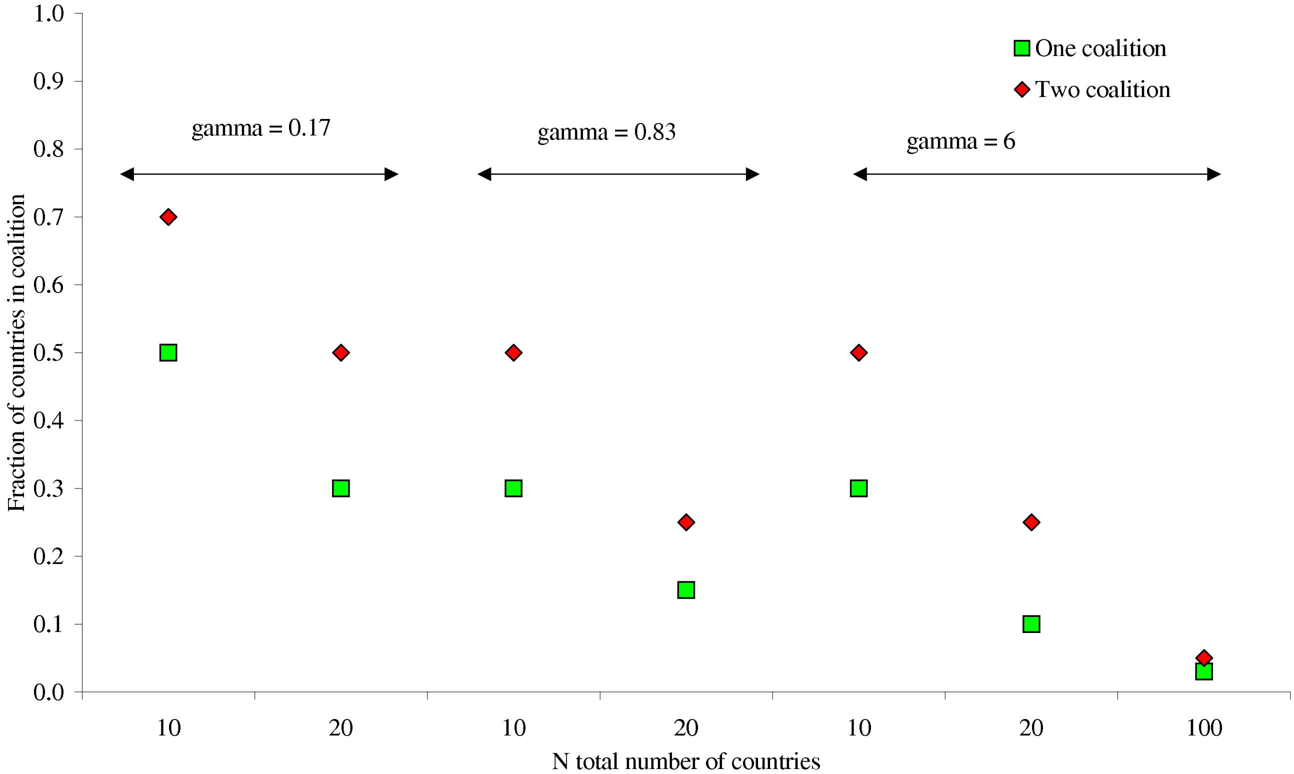

Figure 1.17: Coalition size as function of N and γ for one and two self-enforcing IEA.

Appendix

We present below a detailed description of our simulation.

Table (1.3) gives the total profit (Π) and global abatement level (Q) for noncooperative behavior ($\alpha = 0$) and cooperative behavior ($\alpha = 1$). Cooperation brings higher welfare and lower emissions.

Table (1.3) also shows the net benefit and the abatement level of a representative country of signatories coalition (C_s) as well as of a representative country of nonsignatories (C_n) when α is maximized *in the case of one self-enforcing IEA*. It shows the global net benefits Π and the global abatement level Q. As in Barrett(1994a) the coalition is larger if stakes are lower.

Insert Table 3 here.

Table (1.3) also shows the net benefit and the abatement level of a representative country of signatories coalition (C_{s1}, C_{s2}) as well as of a representative country of nonsignatories (C_n) when the sum ($\alpha_1 + \alpha_2$) is maximized *in the case of two self-enforcing IEA*. It shows the global net benefits Π and the global abatement level Q too.

We keep $a = 100, c = 0.25, N = 10$ unchanged *and vary* $b > c$ (for $b < c$ see Table (1.4)).

In the first part of the Table (1.3) (b is big compared to c, $\gamma = c/b$ is small and the coalitions are big). An abatement increase by the coalition C_{s2} is offset by abatement decrease by the coalition C_{s1} while the nonsignatories C_n play almost the same role in one and two self-enforcing IEA's. Total abatement goes down by having two coalitions. Total welfare also falls. Note that *single coalition is stable to the deviations of individual countries but not against deviations of a group of countries.*

In the second part of Table (1.3) ($b = 0.5$, b is smaller compared to c, $\gamma = c/b$ is small, the coalitions are still big) the coalition of signatories C_{s2} has the same benefits as the nonsignatories C_n, so we have no change on the environment quality and welfare if compared to one self-enforcing IEA.

In the third part of Table (1.3) (when $b = 0.3, \gamma = c/b$ is almost 1, the coalitions are small) *a second international IEA is benificial.* The coalition of signatories C_{s1} brings more benefits to the environment than the nonsignatories C_n by increasing the total abatement Q (by 1.2 per cent) and also improving the welfare compared to one self-enforcing IEA. But even for this example the increase in the abatement levels of C_{s1} is partly offset by the decrease in the abatement levels of C_{s2}, while the nonsignatories C_n play the same role in one and two self-enforcing IEA.

In Table (1.4) we introduce the similar results as in Table (1.3) for different values of parameters b, c. We keep $a = 100, N = 10, b = 0.25$ unchanged and *chose* $c > b$. In the first part of Table (1.4) $c = 1.5$, in the second part $c = 1$.

As we see in the first part of the Table (1.4) ($c = 1.5$, c is relatively big compared to b, $\gamma = c/b$ is big, the coalitions are small) but *the second self-enforcing IEA brings significant improvement compared to one self-enforcing IEA*. This is due to the fact that the abatement levels of coalition of signatories C_{s2} are much higher than the abatement level of coalition of signatories C_{s1} and nonsignatories C_n.

Insert Table 4 here.

In spite of the fact that abatement increase by the coalition C_{s2} is partly offset by abatement decrease by the nonsignatories C_n and the coalition of signatories C_{s1} we have still the improvement of Q by 34.2 per cent and total profit Π by 26.1 per cent. For $c = 1$ results are similar.

The difference of Q and Π between the two self-enforcing IEA and noncooperative behavior is big in both parts of Table (1.4).

Sensitivity analysis

The difference between the first and the second part of Table (1.5) is that we keep $b = 1.5, c = 0.25, N = 10$ unchanged but *we change a 10 times bigger, from* $a = 100$ *to* $a = 1000$.

Insert Table 5 here.

As we see the total profit Π is 100 times bigger (also individual profit π), the total abatement level Q is 10 times bigger (also individual abatement level q), but the size of signatories coalition remains constant.

The same analysis apply for the difference between noncooperative and cooperative behavior when a goes 100 to 1000. This is clearly concluded from the analytical formula for noncooperative and cooperative behavior.

In Table (1.6) we introduce the similar results as in Table (1.3) and Table (1.4) but *choosing* b, c *much bigger than before (from 10 to 100 times bigger).*

In the first part of Table (1.6) we rewrite result of the last part of Table (1.3) and in the second part of it we keep $a = 100, N = 10$ unchanged, but we change b, c 100 times bigger (from $b = 0.3$ to $b = 30$, from $c = 0.25$ to $c = 25$). As we see the first and second are qualitatively the same. In both parts two self-enforcing IEA brings a little improvement in environmental quality and welfare compared one self-enforcing IEA. The value of Q (and individual q) remains the same, but no surprise that the total profit Π (and individual π too) is 100 times bigger. The size of signatories coalition and nonsignatories remains constant.

In the third part of Table (1.6) we keep $a = 100, N = 10$ unchanged, but we change b around 17 times and c 10 times (from $b = 17.5$ to $b = 300$, from $c = 10$ to $c = 300$).

Insert Table 6 here.

As we see the third and forth part of Table (1.6) are still qualitatively similar. In both parts the second self-enforcing IEA brings a little improvement in environmental quality and welfare compared one self-enforcing IEA but in stead of a significant carbon-leakage phenomena we have only a smaller carbon-leakage phenomena. But here we have the value of Q (and individual q too) is around 1.3 times smaller, but the total profit Π (and individual π too) is around 15 times bigger. The size of signatories coalition is a little smaller.

The difference between the fifth and sixth part of Table (1.6) is that we increase b, c by 100 times (from $b = 0.25$ to $b = 25$, from $c = 1.5$ to $c = 150$). We keep $a = 100$ and $N = 10$ unchanged. The difference in the results are identically the same as for the first part of Table (1.6) so we do not repeat the previous analysis.

The difference between the first part and the second part of Table (1.7) is that we keep $a = 100, b = 1.5, c = 0.25$ unchanged but *we change* N *form 10 to 20.* We have an improvement of welfare by 0.5 per cent but a little decrease of environmental quality. The individual abatement levels and profit are decreased by factor 2.

Insert Table 7 here.

The number of first coalition of signatories is two times bigger, while the second signatories coalition C_{s2} has one country more. In the first part of Table (1.7) the two self-enforcing IEA's benefit environment, but worsening the welfare while in the second part the two self-enforcing IEA's is working identically the same as one self-enforcing IEA. By increasing N the difference between one and two self-enforcing IEA decreases.

The difference between the third part and the fourth part of Table (1.7) is that we keep $a = 100, b = 0.3, c = 0.25$ unchanged but we change N from 10 to 20. We have a small decrease of welfare and a little decrease of environmental quality. Individual abatement levels and profit are lower by factor 2. The number of first and the second coalition signatories are the same. In the third part of Table (1.7) the two self-enforcing IEA is working better than one self-enforcing IEA. In the fourth part, the difference between one and two IEA's is larger than in the third part.

The difference of Q *and* Π *between the two self-enforcing IEA and noncooperative behavior* is smaller when N is bigger. By increasing N, the Q and Π for noncooperative behavior get bigger.

We introduce Table (1.8) in order to see that *the significant improvement in environment equality and welfare that we see in Table (1.4) are significantly reduced when we have a much bigger* N. The difference between the first part, the second and the third part of Table (1.8) is that we keep $a = 100, b = 25, c = 150$ unchanged but we change N form 10 to 20 and then to 100.

Insert Table 8 here.

As we can see the second s.e IEA brings significantly more improvement on environment equality and welfare (Q is improved by more than 34 per cent and Π by more than 26 per cent) when $N = 10$ (first part of Table (1.8)). When $N = 20$ (second part of Table (1.8)) we have relatively less improvement on environment equality and welfare (Q is improved by more than 18 per cent and Π by more than 15 per cent), compared with the case when $N = 10$. When $N = 100$ (third part of Table (1.8)) we have significantly less improvement on environment equality and welfare (Q is improved only by 1.14 per cent and Π only by 1.06 per cent), compared with the case when $N = 10$. When we change N we have the other changes we have already mentioned in the discussion of Table (1.7)).

Summary

When γ is small we have big coalitions of signatories but *the second self-enforcing IEA worsens the environment quality and welfare compared to one self-enforcing IEA*. When γ gets bigger, there comes a point where *the second self-enforcing IEA works the same as one self-enforcing IEA* but we have smaller coalitions of signatories. When $\gamma \approx 1$ *the second self-enforcing IEA brings a little improvement in environment quality and welfare compared to one self-enforcing IEA* in spite of the fact that the coalitions of signatories are even smaller. Only when γ is big and N is not so big *the second self-enforcing IEA brings significant improvement in environment and welfare compared one self-enforcing IEA*, but the increase of N reduced drastically the improvement. Having a bigger N (when γ is small) increases environmental quality but reduces welfare. A bigger N (when $\gamma \approx 1$) worsens a little the environment and the welfare. The individual q andπ, of both signatories and nonsignatories, decrease by the same amount (relatively) as N increases. A bigger a means better environmental equality and welfare. A bigger b and c means always a better welfare; if $b > c$ we have a little decrease in environmental equality; if $b \leq c$ we have a constant level of environmental equality.

The values of parameters for which two self-enforcing IEA brings a significant improvement compared to one self-enforcing IEA are: a big a, b and c (they guarantee good environmental quality and welfare level) and $b \leq c$ as well as a relatively small N (they guarantee two self-enforcing IEA brings a big improvement compared to one self-enforcing IEA).

Table 1.3: Comparing the abatement levels and benefits between one and two self-enforcing IEA *for different **b***. (*The symbol * we use to mark stability abatement values, and it is valid for all tables*).

a second s.e IEA reduces welfare, increases abatement									
a	b	c	N						
100	1.5	0.25	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	8.57	-	-	725.51	85.7	7255.1
1	-	9.84	-	-	737.7	-	-	98.4	7377.0
0.5*	-	9.7*	-	7.7*	725.8*	-	730.0*	87.09*	7279.1*
0.5*	0.2*	10.6*	5.5*	7.7*	723.6*	733.7*	730.1*	87.11*	7275.5*
a second s.e IEA reduces welfare and abatement									
a	b	c	N						
100	1	0.25	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	8	-	-	472	80	4720
1	-	9.76	-	-	487.8	-	-	97.6	4878.0
0.4*	-	8.9*	-	7.6*	472.2*	-	474.9*	81.1*	4738.1*
0.4*	0.2*	9.6*	5.9*	7.7*	470.1*	477.2*	474.2*	80.79*	4731.6*
a second s.e IEA leaves things unchanged									
a	b	c	N						
100	0.5	0.25	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	6.67	-	-	216.67	66.7	2166.7
1	-	9.52	-	-	238.1	-	-	95.2	2381.0
0.3*	-	7.9*	-	6.3*	216.9*	-	219.8*	68.3*	2189.2*
0.3*	0.2*	7.9*	6.3*	6.3*	216.9*	219.8*	219.8*	68.3*	2189.2*
a second s.e IEA increases welfare and abatement									
a	b	c	N						
100	0.3	0.25	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	5.45	-	-	115.29	54.5	1152.9
1	-	9.23	-	-	138.46	-	-	92.3	1384.6
0.3*	-	8.1*	-	4.9*	116.4*	-	121.5*	58.8*	1199.6*
0.3*	0.2*	7.7*	6.1*	4.9*	118.0*	120.8*	122.4*	59.5*	1207.7*

Table 1.4: Comparing the abatement levels and benefits between one and two self-enforcing IEA *for different* ***c***.

a second s.e IEA increases welfare and abatement									
a	b	c	N						
100	0.25	1.5	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0.2*	-	2.5*	-	1.4*	32.5*	-	35.6*	16.1*	349.6*
0.3*	0.2*	3.4*	2.4*	1.3*	39.4*	43.9*	46.9*	21.6*	440.7*
a second s.e IEA increases welfare and abatement									
a	b	c	N						
100	0.25	1	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	2	-	-	43	20	430
1	-	7.14	-	-	89.29	-	-	71.4	892.9
0.2*	-	3.2*	-	1.9*	43.8*	-	47.2*	22.1*	465.3*
0.3*	0.2*	4.4*	3.2*	1.8*	51.4*	56.1*	59.6*	28.5*	564.2*

Table 1.5: Comparing the abatement levels and benefits between one and two self-enforcing IEA *for different* ***a***.

a second IEA reduces welfare and abatement									
a	b	c	N						
100	1.5	0.25	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	8.57	-	-	725.51	85.7	7255.1
1	-	9.84	-	-	737.7	-	-	98.4	7377.0
0.5*	-	9.7*	-	7.7*	725.8*	-	730.0*	87.09*	7279.1*
0.5*	0.2*	10.6*	5.5*	7.7*	723.6*	733.7*	730.1*	87.11*	7275.5*
a	b	c	N						
1000	1.5	0.25	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	85.71	-	-	72551.02	857.1	725510.2
1	-	98.36	-	-	73770.49	-	-	983.6	737704.9
0.5*	-	96.7*	-	77.4*	72580.6*	-	73002.1*	870.9*	727913.6*
0.5*	0.2*	105.7*	55.2*	77.3*	72356.7*	73372.7*	73006.5*	871.1*	727549.1*

Table 1.6: Comparing the abatement levels and benefits between one and two self-enforcing IEA *for big* $\boldsymbol{b}$ *and* $\boldsymbol{c}$.

a second IEA improves welfare and abatement									
a	b	c	N						
100	0.3	0.25	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	5.45	-	-	115.29	54.5	1152.9
1	-	9.23	-	-	138.46	-	-	92.3	1384.6
0.3*	-	8.1*	-	4.9*	116.4*	-	121.5*	58.8*	1199.6*
0.3*	0.2*	7.7*	6.1*	4.9*	118.0*	120.8*	122.4*	59.5*	1207.7*
a	b	c	N						
100	30	25	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0.3*	-	8.1*	-	4.9*	11640.0*	-	12147.8*	58.8*	119957.3*
0.3*	0.2*	7.7*	6.1*	4.9*	11801.7*	12076.6*	12242.8*	59.4*	120772.3*
a second IEA improves welfare and abatement									
a	b	c	N						
1000	17.5	10	100						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0.03*	-	7.1*	-	6.4*	75729.8*	-	75777.5*	637.1*	7577608.6*
0.04*	0.03*	9.3*	7.2*	6.3*	75837.0*	76016.1*	76075.8*	641.8*	7606444.3*
a	b	c	N						
1000	300	300	100						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0.03*	-	7.6*	-	5.0*	1122251.9*	-	1127121.6*	503.9*	112697554.3*
0.03*	0.02*	7.4*	7.6*	4.9*	1128322.1*	1127920.9*	1132976.9*	507.8*	113268553.0*
a second IEA improves welfare and abatement									
a	b	c	N						
100	0.25	1.5	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0.2*	-	2.5*	-	1.4*	32.5*	-	35.6*	16.1*	349.6*
0.3*	0.2*	3.4*	2.4*	1.3*	39.4*	43.9*	46.9*	21.6*	440.7*
a	b	c	N						
100	25	150	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0.2*	-	2.5*	-	1.4*	3248.4*	-	3558.3*	16.1*	34962.8*
0.3*	0.2*	3.4*	2.4*	1.3*	3942.6*	4385.2*	4693.4*	21.6*	44065.4*

Table 1.7: Comparing the abatement levels and benefits between one and two self-enforcing IEA *for different* ***N***.

a second IEA reduces welfare and abatement									
a	b	c	N						
100	1.5	0.25	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	8.57	-	-	725.51	85.7	7255.1
1	-	9.84	-	-	737.7	-	-	98.4	7377.0
0.5*	-	9.7*	-	7.7*	725.8*	-	730.0*	87.09*	7279.1*
0.5*	0.2*	10.6*	5.5*	7.7*	723.6*	733.7*	730.1*	87.11*	7275.5*
a	b	c	N						
100	1.5	0.25	20						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	8.57	-	-	730.1	85.7	7301.0
1	-	9.92	-	-	-	-	743.8	99.2	7438.0
0.3*	-	4.76*	-	4.12*	365.09*	-	365.79*	86.26*	7311.65*
0.3*	0.2*	4.76*	4.12*	4.12*	365.09*	365.79*	365.79*	86.26*	7311.65*
a second IEA increases welfare and abatement									
a	b	c	N						
100	0.3	0.25	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	5.45	-	-	115.29	54.5	1152.9
1	-	9.23	-	-	138.46	-	-	92.3	1384.6
0.3*	-	8.1*	-	4.9*	116.4*	-	121.5*	58.8*	1199.6*
0.3*	0.2*	7.7*	6.1*	4.9*	118.0*	120.8*	122.4*	59.5*	1207.7*
a	b	c	N						
100	0.3	0.25	20						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	5.45	-	-	117.15	54.5	1171.5
1	-	9.6	-	-	144	-	-	96.0	1440
0.15*	-	3.90*	-	2.62*	58.8*	-	59.8*	56.3*	1193.0*
0.15*	0.1*	3.87*	2.75*	2.62*	58.9*	59.8*	59.9*	56.4*	1194.3*

Table 1.8: Comparing the abatement levels and benefits between a successful two self-enforcing IEA *for different **N***.

a second IEA increases welfare and abatement									
a	b	c	N						
100	25	150	10						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	1.43	-	-	3163.3	14.3	31632.7
1	-	6.25	-	-	7812.5	-	-	62.5	78125
0.2*	-	2.5*	-	1.4*	3248.4*	-	3558.3*	16.1*	34962.8*
0.3*	0.2*	3.4*	2.4*	1.3*	3942.6*	4385.2	4693.4*	21.6*	44065.4*
a	b	c	N						
100	25	150	20						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	0.71	-	-	1619.9	14.3	32398
1	-	3.85	-	-	4807.7	-	-	76.9	96153.9
0.1*	-	1.2*	-	0.7*	1716.1*	-	1518.1*	15.2*	34171.3*
0.15*	0.1*	1.8*	1.2*	0.7*	1811.6*	1937.3*	2013.0*	18.0*	39504.3*
a	b	c	N						
100	25	150	100						
α_1	α_2	q_{s1}	q_{s2}	q_n	π_{s1}	π_{s2}	π_n	Q	Π
0	-	-	-	0.14	-	-	330.1	14.3	33010.2
1	-	0.94	-	-	1179.2	-	-	94.3	117924.5
0.03*	-	0.37*	-	0.14*	333.9*	-	342.5*	14.86	34219.7*
0.03*	0.02*	0.36*	0.24*	0.14*	337.7*	343.2*	346.1*	15.03*	34583.0*

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Chapter 2

Toward Farsightedly Stable International Environmental Agreements

Toward Farsightedly Stable International Environmental Agreements

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Abstract

The stability of International Environmental Agreements (IEA) is analyzed by using game theory. The integrated assessment model FUND provides the cost-benefit payoff functions of pollution abatement for sixteen different world regions. The farsighted stability concept of Chwe (1994) is used and solved by combinatorial algorithms. Farsighted stability assumes perfect foresight of the players and predicts which coalitions can be formed when players are farsighted. All farsightedly stable coalitions are found, and their improvement to environment and welfare is considerable. The farsightedly stable coalitions are refined further to preferred farsightedly stable coalitions, which are coalitions where the majority of coalition members reach higher profits in comparison to any other farsightedly stable coalitions. Farsightedly stable coalitions contribute more to the improvement of environment and welfare in comparison to D'Aspremont stable ones (D'Aspremont.etal 1983). Considering multiple farsighted stable coalitions, participation in coalitions for environmental protection is significantly increased, which is an optimistic result of our game theoretical model.

Keywords: game theory, integrated assessment modeling, farsighted stability, coalition formation, d'Aspremont stability.

JEL: C02, C72, H41

2.1 Introduction

The body of literature on International Environmental Agreements (IEA) has two conflicting views. One is based on cooperative game theory and concludes that the grand coalition is stable, by assuming transferable utility, then using the γ-core concept and implementing transfers to solve the heterogeneity of the countries involved (Chander & Tulkens 1997, 2006, Eyckmans & Tulkens 2003, Chander 2007). This represents an optimistic view of the possibility of international cooperation on solving global environmental problems. The other view is rooted in the non-cooperative game theory and became the dominant path in the literature (Barrett 1994, 2003, Botteon & Carraro 2001, Osmani & Tol 2005, Finus.etal 2006, Rubio & Ulph 2006, McGinty 2007). The usual approach of non-cooperative game theory to stable IEAs is based on the idea developed for cartel stability (d'Aspremont et al. (1983)) and requires so-called internal and external stability. Internal stability means that a country does not have an incentive to leave the coalition, while external stability means that a country does not have an incentive to join the coalition. This part of the literature reaches the conclusion that the size of a stable coalition is typically very small, thus representing a pessimistic view of global environmental goods.

In this work, the IEAs are analyzed by using the farsighted stability concept within the framework of mixed non-cooperative and cooperative game theory. We investigate what outcomes are stable, which implies that they cannot be replaced by any coalition of rational, farsighted and selfish countries. The selfishness of players shapes the aspects of *non-cooperative approach*. The idea of farsightedness means that one should check for multi-step stability by comparing the profits of a coalition member after a series of deviations has come to an end. The deviation is possible only if players (regions) display *cooperate attitude (by forming a coalition)* to each-other in order to increase their welfare.
Farsighted stability developed further the notation of stable sets of von Neumann & Morgenstern (1947). Stable sets are defined to be self-consistent. The notion is characterized by internal and external stability. Internal stability guarantees that the solution set is free from inner contradictions, that is, any two outcomes in the solution set cannot dominate each other and external stability guarantees that every outcome excluded from the solution is accounted for, that is, it is dominated by some outcome inside the solution. Harsanyi (1974) criticizes the von Neumann and Morgenstern solution also for its failing to incorporate foresight. He introduced the concept of indirect dominance to capture foresight. An outcome indirectly dominates another, if there exists a sequence of outcomes starting from the dominated outcome and leading to the dominating one, and at each stage of the sequence the group of players required to enact the inducement prefers the final outcome to its status quo. His criticism inspired a series of works on abstract environments including among others those of Chwe (1994), Mariotti (1997) and Xue (1998).
Chwe (1994) introduces the notation of farsighted stability which is applied to the problem of IEAs by Diamantoudi & Sartzetakis (2002) and by Eyckmans (2003). Diamantoudi & Sartzetakis (2002) consider identical countries while asymmetric countries are taken into account in our model. Eyckmans (2003) studies only single farsightedly stable coalitions while we allow multiple farsightedly stable coalitions. In addition, a more systematic way of finding farsightedly stable coalitions is introduced in our approach (as we have 16 different world regions, Eyckmans consider only 5 world regions).
The welfare functions of sixteen world regions are taken from the Climate Framework for Uncertainty, Negotiation and Distribution model FUND (see Section 4.2).
Solving farsighted stability by using combinatorial algorithms, we find all farsightedly stable coalitions. We show that by applying FUND, two farsightedly stable coalitions can be formed. The number of regions in both coalitions is around two thirds of all regions, and they improve welfare and abatement levels significantly . This is one of the few relatively optimistic results of non-cooperative game theory.
Another contribution of this paper is the further extension of the farsighted stability concept to preferred farsighted stability. The preferred farsightedly stable coalition is a farsightedly stable coalition where the majority of country members reach higher profits in comparison to any other farsightedly stable coalition[1].
In section two we present the FUND model. Our algorithms for finding the farsighted stable single coalitions are introduced in the third section. In section four we discuss the refinement of the farsighted stability to preferred farsighted stability which help us to build some possible "histories" of a single coalition formation. In the next section, the improvements to welfare and abatement levels of single farsightedly stable coalitions are presented. We continue with a short comparison (for welfare and abatement improvements) between D'Aspremont stable coalitions[2] and farsightedly stable coalitions. In sixth section we raise the multi-coalition question and show which coalitions can be formed and how much they improve welfare and abatement levels. Multiple D'Aspremont stable coalitions are also briefly considered. Section seven provides our conclusions. Appendix eight discusses the detailed algorithms for finding farsighted stable coalitions and presents a small part of our numerical computations. In Appendix nine some results and figures are presented.

2.2 FUND model

This paper uses version 2.8 of the Climate Framework for Uncertainty, Negotiation and Distribution (FUND). Version 2.8 of FUND corresponds to version 1.6, described and applied by Tol (1999a,b, 2001, 2002c), except for the impact module, which is described by Tol (2002a,b) and updated by Link and Tol (2004). A further difference is that the current version of the model distinguishes 16 instead of 9 regions. Finally, the model considers emission reduction of methane and nitrous oxide as well as carbon dioxide, as described by Tol (forthcoming[a]).
Essentially, FUND consists of a set of exogenous scenarios and endogenous perturbations. The model

[1] We consider only *economic incentives* that a region has to join a coalition for environmental protection. Other factors like commitment to cooperation are not taken into account.
[2] For an introduction of D'Aspremont stability please refer to Barrett (1994).

distinguishes 16 major regions of the world, viz. the United States of America (USA), Canada (CAN), Western Europe (WEU), Japan and South Korea (JPK), Australia and New Zealand (ANZ), Central and Eastern Europe (EEU), the former Soviet Union (FSU), the Middle East (MDE), Central America (CAM), South America (LAM), South Asia (SAS), Southeast Asia (SEA), China (CHI), North Africa (NAF), Sub-Saharan Africa (SSA), and Small Island States (SIS). The model runs from 1950 to 2300 in time steps of one year. The prime reason for starting in 1950 is to initialize the climate change impact module. In FUND, the impacts of climate change are assumed to depend on the impact of the previous year, this way reflecting the process of adjustment to climate change. Because the initial values to be used for the year 1950 cannot be approximated very well, both physical and monetized impacts of climate change tend to be misrepresented in the first few decades of the model runs. The period of 1950-1990 is used for the calibration of the model, which is based on the IMAGE 100-year database (Batjes & Goldewijk, 1994). The period 1990-2000 is based on observations (WRI, 2000). The climate scenarios for the period 2010-2100 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett et al., 1992). The 2000-2010 period is interpolated from the immediate past, and the period 2100-2300 extrapolated.

The scenarios are defined by the rates of population growth, economic growth, autonomous energy efficiency improvements as well as the rate of decarbonization of the energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from land use change, methane and nitrous oxide. The scenarios of economic and population growth are perturbed by the impact of climatic change. Population decreases with increasing climate change related deaths that result from changes in heat stress, cold stress,malaria, and tropical cyclones. Heat and cold stress are assumed to have an effect only on the elderly, non-reproductive population. In contrast, the other sources of mortality also affect the number of births. Heat stress only affects the urban population. The share of the urban population among the total population is based on the World Resources Databases (WRI, 2000). It is extrapolated based on the statistical relationship between urbanization and per-capita income, which are estimated from a cross-section of countries in 1995. Climate-induced migration between the regions of the world also causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The market impacts are dead-weight losses to the economy. Consumption and investment are reduced without changing the savings rate. As a result, climate change reduces long-term economic growth, although consumption is particularly affected in the short-term. Economic growth is also reduced by carbon dioxide abatement measures. The energy intensity of the economy and the carbon intensity of the energy supply autonomously decrease over time. This process can be accelerated by abatement policies, an option not considered in this paper.

The endogenous parts of FUND consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, the impact of carbon dioxide emission reductions on the economy and on emissions, and the impact of the damages to the economy and the population caused by climate change. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is represented by the five-box model of Maier-Reimer and Hasselmann (1987). Its parameters are taken from Hammitt et al. (1992). The model also contains sulphur emissions (Tol, forthcoming[a]).

The radiative forcing of carbon dioxide, methane, nitrous oxide and sulphur aerosols is determined based on Shine et al. (1990). The global mean temperature T is governed by a geometric build-up to its equilibrium (determined by the radiative forcing RF), with a half-life of 50 years. In the base case, the global mean temperature rises in equilibrium by 2.5C for a doubling of carbon dioxide equivalents. Regional temperature follows from multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs (Mendelsohn et al., 2000). The global mean sea level is also geometric, with its equilibrium level determined by the temperature and a half-life of 50 years. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario of Kattenberg et al. (1996).

The climate impact module, based on Tol (2002b,c) includes the following categories: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems. Climate change related damages can be attributed to either the rate of change (benchmarked at 0.04C/yr) or the level of change (benchmarked at 1.0C). Damages from the rate of temperature change slowly fade, reflecting adaptation (cf. Tol, 2002c). People can die prematurely due to temperature stress or vector-borne diseases, or they can migrate because of sea level rise. Like all impacts of climate change, these effects are monetized. The value of a statistical life is set to be 200 times the annual per capita

income. The resulting value of a statistical life lies in the middle of the observed range of values in the literature (cf. Cline, 1992). The value of emigration is set to be 3 times the per capita income (Tol, 1995, 1996), the value of immigration is 40 per cent of the per capita income in the host region (Cline, 1992). Losses of dryland and wetlands due to sea level rise are modelled explicitly. The monetary value of a loss of one square kilometre of dryland was on average $4 million in OECD countries in 1990 (cf. Fankhauser, 1994). Dryland value is assumed to be proportional to GDP per square kilometre. Wetland losses are valued at $2 million per square kilometre on average in the OECD in 1990 (cf. Fankhauser, 1994). The wetland value is assumed to have logistic relation to per capita income. Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.
Other impact categories, such as agriculture, forestry, energy, water, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their 'natural' units (cf. Tol, 2002b). Impacts of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, which is determined by a variety of factors, including plant physiology and the behaviour of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative (cf. Tol, 2002c). The impacts of climate change on coastal zones, forestry, unmanaged ecosystems, water resources, diarrhoea malaria, dengue fever, and schistosomiasis are modelled as simple power functions. Impacts are either negative or positive, and they do not change sign (cf. Tol, 2002c). Vulnerability to climate change changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth), heat-related disorders (with urbanization), and ecosystems and health (with higher per capita incomes). Other systems are projected to become less vulnerable, such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) (cf. Tol, 2002c).
Note that we make use of data only for the year 2005. This is sufficient as static game theory is used but with a sophisticated stability concept.

2.2.1 The Welfare function of the FUND model

We approximate the FUND model with a linear benefit/quadratic cost structure for the analysis of coalition formation. Specifically, the abatement cost function is represented as:

$$C_i = \alpha_i R_i^2 Y_i \tag{2.1}$$

where C denotes abatement cost, R relative emission reduction, Y gross domestic product, indexes i denotes regions and α is the cost parameter. The benefit function is approximated as:

$$B_i = \beta_i \sum_{j}^{n} R_j E_j \tag{2.2}$$

where B denotes benefit, β the marginal damage costs of carbon dioxide emissions and E unabated emissions. Table (5.1) gives the parameters of Equations (5.1) and (5.2) as estimated by FUND. Moreover, the profit π_i of a country i is given as:

$$\pi_i = B_i - C_i = \beta_i \sum_{j}^{n} R_j E_j - \alpha_i R_i^2 Y_i \tag{2.3}$$

The second derivative of $d^2\pi_i/dR_i^2 = -2\alpha_i < 0$ as $\alpha_i > 0$. It follows that the profit function of every country i is strictly concave, and as a consequence has a unique maximum. Hence, the non-cooperative optimal emission reduction is found from first order optimal condition:

$$d\pi_i/dR_i = \beta_i E_i - 2\alpha_i R_i Y_i = 0 \Rightarrow R_i = \beta_i E_i/(2\alpha_i Y_i) \tag{2.4}$$

Table 2.1: Our data from the year 2005, where α is the abatement cost parameter (unitless), β the marginal damage costs of carbon dioxide emissions (in dollars per tonne of carbon) E the carbon dioxide emissions (in billion metric tonnes of carbon) and Y gross domestic product, in billions US dollars. Source: FUND

	α	β	E	Y
USA	0.01515466	2.19648488	1.647	10399
CAN	0.01516751	0.09315600	0.124	807
WEU	0.01568000	3.15719404	0.762	12575
JPK	0.01562780	-1.42089104	0.525	8528
ANZ	0.01510650	-0.05143806	0.079	446
EEU	0.01465218	0.10131831	0.177	407
FSU	0.01381774	1.27242378	0.811	629
MDE	0.01434659	0.04737632	0.424	614
CAM	0.01486421	0.06652486	0.115	388
LAM	0.01513700	0.26839935	0.223	1351
SAS	0.01436564	0.35566631	0.559	831
SEA	0.01484894	0.73159104	0.334	1094
CHI	0.01444354	4.35686225	1.431	2376
NAF	0.01459959	0.96627119	0.101	213
SSA	0.01459184	1.07375825	0.145	302
SIS	0.01434621	0.05549814	0.038	55

If a region i is in a coalition with region j, the optimal emission reduction is given by:

$$d\pi_{i+j}/dR_i = 0 \Rightarrow E_i(\beta_i + \beta_j) - 2\alpha_i R_i Y_i = 0 \Rightarrow R_i = (\beta_i + \beta_j)E_i/(2\alpha_i Y_i) \quad (2.5)$$

Thus, the price for entering a coalition is higher emission abatement at home. The return is that the coalition partners also raise their abatement efforts.
Note that our welfare functions are orthogonal. This indicates that the emissions change of a country do not affect the marginal benefits of other countries (that is the independence assumption). In our game, countries outside the coalition benefit from the reduction in emissions achieved by the cooperating countries, but they cannot affect the benefits derived by the members of the coalition. As our cost-benefit functions are orthogonal our approach does not capture the effects of emissions leakage. Even so our cost benefit functions are sufficiently realistic as they are an approximation of the complex model FUND and our procedure of dealing with farsighted stability is also general and appropriate for non-orthogonal functions.

2.3 Our model

There are 16 world regions (we name the set of all regions by N_{16}) in our game theoretic model of IEAs (or coalitions), which are shown in the first column of Table 5.1. At the first level, the link between the economic activity and the physical environment is established in order to generate the integrated assessment model. This link is established through a social welfare function calibrated to the FUND model (see equation 5.7). The social welfare function captures the difference between the profit from pollution and the environmental damage. Following this approach, countries play a two stage-game. In the first stage, each country decides whether to join the coalition $C \subseteq N_{16}$ and become a signatory (or coalition member) or stay singleton and non-signatory (*membership game*). These decisions lead to *coalition structure* S with c coalition-members and *16-c* non-members. *A coalition structure* fully describes how many coalitions are formed (presently we assume that we have one), how many members each coalition has and how many singleton players there are. In the second stage, every country decides on emissions (*strategic game*). Within the coalition, players play cooperatively (by maximizing their joint welfare) while the coalition and single countries compete in a non cooperative way (by maximizing their own welfare). Every coalition C is assigned a real number $v(C)$ (called the characteristic function).

Definition 2.1 *The* ***characteristic function*** *of our 16-player game (played by* c *and* $16-c$ *players, where* c *is cardinality of coalition* C*) is a real-valued function:*
$v(C) : C \to \Re$,
$v(C) = max(\sum_1^c \pi_i) \quad \forall i \in C, \quad C \subset N_{16}, \quad c \leq 16.$

The characteristic function is simply the total profit that coalition members reach by maximizing their joint welfare. As the π_i are strictly concave, their sum is also strictly concave, which simplifies the maximization problem. The game satisfies the superadditivity property:

Definition 2.2 *A game is superadditive if for any two coalitions,* $C_1 \subset N_{16}$ *and* $C_2 \subset N_{16}$:
$v(C_1 \cup C_2) > v(C_1) + v(C_2) \quad C_1 \cap C_2 = \emptyset.$

The *superadditivity property* means that if C_1 and C_2 are disjoint coalitions (here C_1 and C_2 can be single players too), it is clear that they should accomplish at least as much by joining forces as by remaining separate. However the game *very frequently (but not always)* exhibits *positive spillovers:*

Definition 2.3 *A game exhibits positive spillover property if and only if for any two coalitions* $C_1 \subset N_{16}$ *and* $C_2 \subset N_{16}$ *such that* $C_1 \nsubseteq C_2$ *and* $C_2 \nsubseteq C_1$ *we have:*
$\forall k \notin C_1 \cup C_2 \quad v_k(C_1 \cup C_2) > v_k(C_1) \wedge v_k(C_1 \cup C_2) > v_k(C_2)$

It indicates that there is an external gain (C_1 and C_2 may be single players) or a positive spillover from cooperation, making free-riding (i.e., not joining $C_1 \cup C_2$) attractive. It implies that every player $k \notin C_1 \cup C_2$ has higher profit when two coalitions C_1 and C_2 cooperate in comparison to the situation where two coalitions remain separated. It indicates that from a non-signatory's point of view (player k here), the most favorable situation is the one in which all other countries take part in the coalition (except k). The positive spillover property is usually satisfied except for some coalitions that contain as members Japan & South Korea or Australia & New Zealand, which have negative marginal benefits (negative β's) from pollution abatement.
As our game is formally defined we return to our central question, namely farsighted stability. In our model framework, farsighted stability is mainly based on two arguments. The first one is the inducement process, which will be defined in the next subsection. The inducement raises the question: Can a subset of the members of our coalition improve their welfare (with the help of non-members or not) by forming a new coalition? The players are farsighted in the first sense that they check all possible ways (this is done by defining precisely the inducement process) for forming a new coalition in order to improve their welfare. The second argument is a behavioral assumption for the farsighted players that deters free riding. We assume that our players are farsighted in the sense that they refuse to free-ride because the other members of coalition can act similarly and this will ultimately result in a welfare decrease for all.

2.3.1 Farsighted stability and single farsightedly stable coalitions

In the first stage, the formation of *a single farsightedly stable coalition* is considered. As we will consider only profitable coalitions, we define them from the beginning.

Definition 2.4 *The situation in which each country maximizes its own profit, and the maximum coalition size is unity is referred to as the atom structure.*

It is a standard Nash equilibrium. A coalition that performs better than the atom-structure is *a profitable coalition.* Only profitable coalitions are tested, which is sufficient to find all single farsightedly stable coalitions (see Observations 2.3.2 and 2.3.3.). The definition of a profitable coalition is introduced below:

Definition 2.5 *A coalition* C *is profitable (or individual rational) if and only if it satisfies the following condition:*

$\forall i \in C \quad \pi(i)_C \geq \pi(i)_{ind}$

$\pi(i)_C$, $\pi(i)_{ind}$ *are the profits of country* i *as a member of* C *and in the atom structure respectively.*

Considering only profitable coalitions also reduces the computational effort required to find farsightedly stable coalitions.
Before presenting our approach of finding farsightedly stable coalitions, the definitions of *inducement process, credible objection, and farsighted stability* are presented below:

Definition 2.6 *A coalition C_n can be induced from any coalition C_1 if and only if:*

- *there exists a change sequence of coalitions $C_1, C_2 \dots C_{n-1}, C_n$ where $\pi_n(i) \geq \pi_1(i) \quad \forall i \in C_n$ and $C_1 \cap C_n \neq \emptyset$*

or

- *there exists a change sequence of coalitions $C_1, C_2 \dots C_{n-1}, C_n$ where $\pi_m(i) \geq \pi_1(i) \quad \forall i \in C_1 \wedge \forall i \notin C_n$ and $C_1 \subset C_2 \subset \, .. \subset C_{n-1} \subset C_n$*

$\pi_n(i)$, $\pi_m(i)$, $\pi_1(i)$ are profits, $\pi_1(i)$ refers to situations with C_1 and $\pi_n(i)$, $\pi_m(i)$ with C_n.

The first part of the inducement definition requires that all countries of the final coalition C_n do not decrease their profits and indirectly assumes that those countries have started the formation of the final coalition. The second part of the definition requires that all countries that leave the initial coalition C_1 (including free-riding) do not decrease their profits.
The definition of credible objection is presented below:

Definition 2.7 *A group of countries G_1 has a credible objection to coalition C_1 if there exists another coalition C_n such that:*

- *C_n can be induced from C_1 and $\pi_n(i) \geq \pi_1(i) \quad \forall i \in G_1$*
- *no group of countries G_n has a credible objection to C_n*

$\pi_n(i)$, $\pi_1(i)$ are profits, $\pi_1(i)$ refers to situations with C_1 and $\pi_n(i)$ with C_n.

A group of countries has a credible objection to a coalition if there exists an inducement process, and moreover this particular inducement process in the final one (or no group of countries has a credible objection to the final coalition). Now, it is possible to state the definition of farsighted stability:

Definition 2.8 *A coalition C is farsightedly stable if no group of countries G has a credible objection to C.*

The definition of farsighted stability is based on the definition of the inducement process (no credible objection signifies that the inducement process has come to an end). This means, one needs to trace the inducement process in order to test whether a coalition is farsightedly stable or not. Definition 4.6 makes clear that there are two main types of inducement process. In the first type, there is a change sequence of coalitions where *the countries in the final coalition* do not decrease their profits. In the second type, there is a change sequence of coalitions where *the countries that leave the initial coalition* do not decrease their profit. There are five classes of inducement process. Three of them belong to the first type of inducement process; the coalition grows bigger; gets smaller; some coalition-members leave coalition and some others join it. The last two classes of inducement process belong to the second type of inducement process. The fourth class is a special one, namely *free-riding.* One or more countries leaves the coalition and increase their welfare. The fifth inducement process is also a special inducement process which occurs only in *non-profitable coalitions* that have at least one country that has a welfare smaller than in the atom structure. Those countries are going to leave the coalition (and increase their welfare) *not due to free-riding* but because the joint welfare is distributed unfairly; there is no credible objection against those countries. Even if the coalition is dissolved and atom structure is reached, their welfare is higher than in the initial non-profitable coalition.
In order to find the farsightedly stable coalitions *all three inducement processes of **the first type** are considered as combinatorial process.* The fourth inducement, free-riding is deterred based on a behavioral assumption. The fifth inducement process occurs only in non-profitable coalitions, and as we discuss only profitable coalitions[3], we do not need to consider it for finding farsightedly stable coalitions. However, the fifth inducement process is necessary in order to prove Observations 2.3.2 and 2.3.3, which help to

[3]Observations 2.3.2 and 2.3.3 make clear that this is sufficient to find all farsightedly stable coalitions.

define (similar to Chwe (1994)) the *Dynamic Large Consistent Set*[4].
We begin by conceiving the three inducement processes of the first type as a combinatorial process. If a coalition gets bigger, it follows that the original members see an increase in profit (or at least no decrease) and the new members see an increase too. We say that *an external inducement* is possible. The definition of external inducement is introduced below:

Definition 2.9 *An external inducement for coalition C_1 is possible if and only if:*

- *exists a change sequence of coalitions $C_1, C_2 .. C_{m-1}, C_m$ such that $C_1 \subset C_2 \subset .. \subset C_{m-1} \subset C_m$*
- $\forall\, i \in C_m \quad \pi_m(i) \geq \pi_1(i)$

$\pi_1(i)$, $\pi_m(i)$ are the profits of country i with C_1 and with C_m respectively.

This can be easily checked by a combinatorial algorithm.

Definition 2.10 *If no external inducement is possible then the coalition is externally farsightedly stable (EFS).*

If a coalition gets smaller, and its remaining members see an increase in profit, we say that *an internal inducement* is possible.

Definition 2.11 *An internal inducement for coalition C_1 is possible if and only if:*

- *there exists a change sequence of coalitions $C_1, C_2 .. C_{m-1}, C_m$ such that $C_1 \supset C_2 \supset .. \supset C_{m-1} \supset C_m$*
- $\forall\, i \in C_m \quad \pi_m(i) \geq \pi_1(i)$

$\pi_1(i)$, $\pi_m(i)$ are the profits of country i with C_1 and with C_m respectively.

This can be easily checked by a combinatorial algorithm too.

Definition 2.12 *If no internal inducement is possible then the coalition is internally farsightedly stable (IFS).*

The third class of coalition inducement occurs when a number of old coalition members leave and a number of new members join the coalition. The new coalition may be larger or smaller than the original one. One needs to check if a part of old coalition members (a sub-coalition), and the new coalition members can increase their profits by forming a coalition together. We call this *a sub-coalition inducement.*

Definition 2.13 *A sub-coalition inducement for coalition C_k is possible if and only if:*

- *exists a change sequence of coalitions $C_1, C_2 .. C_{m-1}, C_m$ such as $C_k \cap C_l \neq \emptyset\ \forall k, l \in [1, .., m]$*
- $\forall\, i \in C_m \quad \pi_m(i) \geq \pi_1(i)$

$\pi_1(i)$, $\pi_m(i)$ are the profits of country i with C_1 and with C_m respectively.

This case requires more combinatorial work to check if a sub-coalition inducement is possible.

Definition 2.14 *If no sub-coalition inducement is possible then the coalition is sub-coalition farsightedly stable (SFS).*

The definition of farsighted stability can be alternatively formulated:

Definition 2.15 *If no internal, external and sub-coalition inducement is possible then the coalition is farsightedly stable.*

We mention some assumptions which are necessary to structure our game theoretical framework.

Assumption 1 *All three inducement processes of first types require that:*

- *the final coalition C can be stable only if all members of C do not decrease their profit*

[4]Note than any inducement process can be expressed as a combination of the five kinds of inducements which are mentioned above (when only one coalition is formed).

- *if the final coalition, which contains* ***m*** *members, is profitable, and the majority of* ***n*** *coalition-members increase their profits, but* ***(m − n)*** *of coalition-members decrease their profits then, the* ***(m − n)*** *coalition-members leave the coalition not due to free-riding, but because the joint welfare is unfairly distributed*

The first part of the assumption is already consistent with the essential definitions of external, internal and sub-coalition farsighted stability[5]. Numerical computation shows that the free riding appears in all profitable coalitions which have at least four members. As a consequence if $n \geq 3$ coalition-members increase their profits, the $(m-n)$ coalition-members which decrease their profits always have the alternative of free-riding, not because they aspire to free-ride, but because the joint welfare is unequally divided. Concerning the case when $n < 3$ coalition-members[6] increase their profits, numerical computation also shows that decreasing coalition size usually results in decreasing profits for the coalition members. This indicates that when $(m - n)$ countries (which decrease their profit) leave the coalition (see footnote 6), there is a real threat that the rest of n coalition members will decrease their profit. It further implies that, there is usually no inducement process where in the final coalition, some coalition members decrease their profit, which is consistent with our assumption.

Assumption 2 *There is no inducement process whereby a coalition is dissolved and replaced by a totally new coalition.*

The reason is the following: in all three inducement processes of the first type the change process is initiated and controlled by at least some of the coalitions members. In case of external inducement, the change process is managed by all previous members and the new members; in case of internal inducement, the change process is governed by a part of coalition members; in case of sub-coalition inducement, the change process is managed by a part of previous coalition members and the new members. It does not make sense to consider the case of coalition dissolution because the inducement process is not controlled by any member of previous coalition which makes it impossible (for member of initial coalition) to plan any improvement in welfare.

Assumption 3 *If the atom structure is reached, then only a profitable coalition can be formed.*

This is consequent to internal, external and sub-coalition inducement where the profit of countries in the final coalition are not decreased[7]. It is evident that the profits of members in a profitable coalition are not decreased in comparison to the profits of those members in the atom structure.

Assumption 4 *Free-riding is deterred based on motivation that originates from experimental game theory.*

One special inducement process is caused by free-riding. As already noted, free-riding is prevented based on reasoning that originates from experimental game theory (Fehr & Gaechter 2000, Ostrom 2000), which predicts that if a player free-rides[8], as the rest of players receive this information, some (not all) of them will also free-ride. This will result in worsening the welfare of every player. We assume that our players (countries in our approach) possess the knowledge that if free-riding appears, it will expand and other players will start to free-ride. This assumption deters free-riding and fits well with farsighted behavior, as it takes into account the counter reaction of other players. As free-riding is prevented based on this behavioral assumption, which implies that there is no free-riding for any coalition, then the inducement caused by free-riding cannot be included in definition of farsighted stability.

Observation 2.3.1 *Definition 5.6 and definition 5.3 are equivalent* ***within our model assumptions*** *1, 2, 3 and 4.*

Proof: Definition 2.7 makes clear that:

no credible objection to coalition $C \Leftrightarrow$ *the inducement process has come to an end*

So definition 5.6 and definition 5.3 both require that all possible coalitions that can be induced are inspected, and as a consequence all possible inducement processes are also considered. It is clear that all possible coalitions that can be induced from coalition C_n can be divided in three categories (C_1, C_2, C_3):

[5] The second part is similar, but not identical, to the fifth inducement process of the second type.

[6] It is necessary to note that $n < 3$ implies $n = 2$, because $n = 1$ does not make sense since the assumption considers that n coalition-members represent the majority of all m members. It indicates further that $m = 3$, because only $m = 3$ satisfies both $m > n$, and the requirement that n be the majority of coalition members .

[7] Please note that only if the initial coalition is a nonprofitable one can the atom structure be reached.

[8] The referenced papers consider behavior of people not of countries as we would wish.

- $C_1 \subset C_n$ which are checked when internal farsighted stability is examined
- $C_2 \supset C_n$ which are tested when external farsighted stability is investigated
- $C_3 \cap C_n \neq \emptyset$ which are inspected when sub-coalition farsighted stability is considered

As a consequence, we know if there exists a credible objection to our coalition C_n, which completes the proof.

It is necessary to clarify that wherever the farsighted stability is mentioned, *we mean farsighted stability in the sense of definition 5.6,* which implies that our model assumptions 1, 2, 3 and 4 are considered. Testing a coalition for farsighted stability means comparing the profit of country members with *the profit of country members of all possible coalitions (that can be induced or not) and finding the coalitions that can be induced.* We mention again as a crucial element of our approach, that coalitions, which contain our initial coalition as a subset, are inspected when the external farsighted stability is tested; the coalitions, that our initial coalition contains as subsets, are inspected when the internal farsighted stability is tested; and the coalitions, which have mutual members with our coalition, are inspected when the sub-coalition farsighted stability is tested. The algorithms of Table (2.5) and Table (2.6) in Appendix 6.5 fully describe the procedure of finding farsightedly stable coalitions. As this is huge combinatorial effort, we often modify the algorithms in order to decrease our computational cost. We limit our attention to coalitions which are profitable, and this is sufficient to find all farsightedly stable coalitions. The following observations make clear that there is no non-profitable farsightedly stable coalitions.

Observation 2.3.2 *Every non-profitable coalition C is farsightedly stable if and only if:*

1. *it contains at least one profitable sub-coalition $C_1 \subset C$.*
2. *there exists an inducement process from coalition C_1 to C and there is no credible objection against C.*

Proof:
First direction: *If a non-profitable coalition C is farsightedly stable* then, there is a profitable sub-coalition $C_1 \subset C$, and there exists an inducement process from coalition C_1 to C and moreover, there is no credible objection against C.
Part 1:
Suppose that every sub-coalition of any non-profitable farsightedly stable (FS) coalition C_1 has a country that receives a lower profit than in atom-structure, then the coalition C_n is not FS. The coalition is not FS because it is possible to build an inducement process:

$$C_1, \,..\,, C_m, Atom_{structure} \text{ as } \forall \;\; C_l \quad 1 \leq l \leq m \quad \exists \text{ a country } i \in C_l \text{ where } \pi_{C_l}(i) < \pi_{Atom_{structure}}(i)$$

The above inducement process is simple. Every country with lower profit than in the atom structure leaves the coalition. As every sub-coalition has one such country, the coalition is not FS (the fifth inducement process of second type occurs). As a consequence coalition C_1 must have a profitable sub-coalition in order to have a chance of being FS, which completes the first part of the proof.
Part 2:
The first part of the proof guarantees us that the set Ψ of all sub-coalitions of C which are profitable is not empty[9]. Therefore, if we define:
$\Psi = (C_j, \,..\,, C_t | C_j \subset C$ and $C_j \;\; is \;\; profitable \;\; \forall \;\; 1 \leq j \leq t)$.
Besides if C is a non-profitable farsightedly stable coalition then:
$\exists \; C_j \in \Psi|$ and there is an inducement process $C_j, \,..\,, C$ that is the final inducement process (that is, there is no credible objection to C).
If the above statement is not true, then the following statement is true:
$\forall \; C_j \in \Psi|$ there is no inducement process $C_j, \,..\,, C$ that is the final inducement process, and consequently C is not a farsightedly stable coalition, which contradicts our starting point and completes the proof.
Second direction: *If the non-profitable coalition C has a profitable sub-coalition $C_1 \subset C$, and there exists an inducement process from coalition C_1 to C and there is no credible objection against C*, then coalition C is farsightedly stable.
Proof: The proof of second direction is almost identical to the first direction, so we omit it.

[9]Note that the non-profitable farsightedly stable coalition C cannot be induced directly from atom structure as at least one country decreases its profit.

Corollary 2.3.1 *If a nonprofitable coalition C_1 is not a farsightedly stable coalition there exists an inducement process $C_1, .. , C_m$ where C_m is a profitable sub-coalition of C_1 or $C_m \equiv Atom_{structure}$.*

Proof: This is a direct consequence of Observation 2.3.1.

Observation 2.3.3 *There is no nonprofitable coalition C which is farsightedly stable.*

Proof: As we find all profitable FS coalitions, we have obtained also profitable sub-coalitions of non-profitable FS coalitions (if there is any non-profitable FS coalition). Starting from these coalitions and considering all possible inducement processes we can reach our non-profitable FS coalition. *Our combinatorics computer programs,* which consider all inducement processes, prove that there is no non-profitable coalitions which is farsightedly stable.

Thus, at the beginning all profitable coalitions, and then all single-farsightedly stable coalitions are found.

2.3.2 Computation results

Finding all profitable coalitions needs a simple algorithm, although the computational effort is considerable. One finds all coalitions and checks if all their members have higher profit in comparison to the atom structure.
The numerical results yield fifteen profitable two-member coalitions. As there are many profitable coalitions, we have numbered them: for instance $2-13$, 2 means that coalition has 2 countries, and 13 means that it is the 13-th in the list of two-member profitable coalitions. The profitable two-member coalitions are:

$(2-1)$	(USA, CHI)	$(2-2)$	(USA, NAF)	$(2-3)$	(USA, SSA)
$(2-4)$	(CAN, SAS)	$(2-5)$	(ANZ, EEU)	$(2-6)$	(ANZ, CAM)
$(2-7)$	(ANZ, SAS)	$(2-8)$	(ANZ, SIS)	$(2-9)$	(EEU, CAM)
$(2-10)$	(EEU, SIS)	$(2-11)$	(FSU, LAM)	$(2-12)$	(CAM, SIS)
$(2-13)$	(CHI, NAF)	$(2-14)$	(CHI, SSA)	$(2-15)$	(NAF, SSA)

The profitable three-member coalitions are introduced below (the superscript "fs" denotes farsightedly stable):

$(3-1)$	(USA, LAM, CHI)	$(3-2)$	(USA, SEA, CHI)
$(3-3)$	$(USA, CHI, NAF)^{fs}$	$(3-4)$	$(USA, CHI, SSA)^{fs}$
$(3-5)$	(USA, NAF, SSA)	$(3-6)$	$(CAN, EEU, SAS)^{fs}$
$(3-7)$	$(CAN, FSU, LAM)^{fs}$	$(3-8)$	$(CAN, CAM, SAS)^{fs}$
$(3-9)$	(CAN, CAM, SIS)	$(3-10)$	$(CAN, SAS, SIS)^{fs}$
$(3-11)$	(JPK, NAF, SSA)	$(3-12)$	$(EEU, CAM, SAS)^{fs}$
$(3-13)$	(EEU, CAM, SIS)	$(3-14)$	$(EEU, SAS, SIS)^{fs}$
$(3-15)$	$(CAM, SAS, SIS)^{fs}$	$(3-16)$	$(CHI, NAF, SSA)^{fs}$

The profitable four-member coalitions are:

$(4-1)$	(USA, LAM, SEA, CHI)	$(4-2)$	(USA, LAM, SEA, SSA)
$(4-3)$	$(USA, LAM, CHI, NAF)^{fs}$	$(4-4)$	$(USA, LAM, CHI, SSA)^{fs}$
$(4-5)$	$(USA, SEA, CHI, NAF)^{fs}$	$(4-6)$	$(USA, SEA, CHI, SSA)^{fs}$
$(4-7)$	$(USA, CHI, NAF, SSA)^{fs}$	$(4-8)$	$(CAN, EEU, CAM, SAS)^{fs}$
$(4-9)$	(CAN, EEU, CAM, SIS)	$(4-10)$	$(CAN, EEU, SAS, SIS)^{fs}$
$(4-11)$	$(CAN, CAM, SAS, SIS)^{fs}$	$(4-12)$	$(EEU, CAM, SAS, SIS)^{fs}$
$(4-13)$	(LAM, SEA, CHI, NAF)	$(4-14)$	(LAM, SEA, CHI, SSA)
$(4-15)$	$(SEA, CHI, NAF, SSA)^{fs}$		

The profitable five-member coalitions are presented below:

$(5-1)$	$(USA, LAM, SEA, CHI, NAF)^{fs}$	$(5-2)$	$(USA, LAM, SEA, CHI, SSA)^{fs}$

$(5-3)$	$(USA, LAM, SEA, NAF, SSA)^{fs}$	$(5-4)$	$(USA, LAM, CHI, NAF, SSA)^{fs}$
$(5-5)$	$(USA, SEA, CHI, NAF, SSA)^{fs}$	$(5-6)$	$(CAN, JPK, LAM, SAS, SSA)$
$(5-7)$	$(CAN, EEU, CAM, SAS, SIS)^{fs}$	$(5-8)$	$(LAM, SEA, CHI, NAF, SSA)^{fs}$

There is only one 1 six-member and only one 1 seven-member profitable coalition:

$(6-1)$	$(USA, LAM, SEA, CHI, NAF, SSA)^{fs}$
$(7-1)$	$(CAN, JPK, EEU, CAM, LAM, NAF, SIS)$

In total, there are 56 profitable coalitions. $\mathbf{Coal_{prof}}$ is the set that contains all 56 profitable coalitions. All profitable coalitions are internally farsightedly stable. By checking for external and sub-coalition stability, we find that we have 28 farsightedly stable coalitions: 1 six-member coalition, 7 five-member coalitions, 10 four-member coalitions and 10 three-member coalitions[10]. $\mathbf{Coal_{fs}}$ is the set that contains all 28 farsightedly stable coalitions.
In the spirit of Chwe (1994), but adapted to our problem framework, we characterize the set of all farsightedly stable coalitions $Coal_{fs}$ as *Dynamic Large Consistent Set (DLCS).*

Definition 2.16 *A set S is the Dynamic Large Consistent Set if and only if:*

- $\forall$ *coalition* $C_1 \notin S$ *exists an inducement process from* C_1 *to* C_n
- *the coalition* $C_n \in S$ *and no group of countries G has a credible objection to* C_n

The definition indicates that any coalition C_1 that does not belong to DLCS is not farsightedly stable, and moreover there exits an inducement process from C_1 to C_n, where $C_n \in DLCS$. Furthermore, this inducement process is the final one (or there is no group of countries G which has a credible objection to C_n).

Observation 2.3.4 *The set of all farsightedly stable coalitions* $\boldsymbol{Coal_{fs}}$ *is the Dynamic Large Consistent Set.*

Proof: Observations 2.3.2, 2.3.3 and Corollary 2.3.1 show that *any non-profitable coalition* leads either to a profitable coalition or to the atom structure. Only profitable coalition can arise from the atom structure according to Assumption 3. Our computer programs prove that every profitable coalition leads to a coalition that belongs to $\mathbf{Coal_{fs}}$ as result of inducement processes, which completes the proof.

As already pointed out, the farsightedly stable coalitions are just a subset of profitable coalitions, which indicates that all farsightedly stable coalitions are profitable[11]. Therefore, farsighted stability is not a function of free-riding (like D'Aspremont myopic stability) *but farsighted stability is a function of profitability* which is difficult to satisfy for a single large coalition. Take coalition (6-1) $(USA, LAM, SEA, CHI, NAF, SSA)$. It is numerically checked that there is no larger profitable coalition that contains coalition (6-1) as subset. This implies that in all coalitions which contains coalition (6-1) as subset, there is at least one country that has a welfare smaller than in the atom structure. Those countries leave the coalition not due to free-riding but because the joint welfare is distributed unfairly (the fifth inducement process of second type occurs). There is no way (even farsighted way)

[10]One peculiar point needs to be clarified further. The coalition(6-1) and its subset, coalition (5-1) are both farsightedly stable. Coalition ((5-1) cannot be induced by coalition (6-1) by free-riding of SSA. We further suppose that when coalition (5-1) is formed, SSA did not join it not due to free-riding but because of some ad-hoc reasons, but not free-riding because a farsighted player does not free-ride. This discussion is valid for every two farsightedly stable coalitions, where one of them is subset of the other. This occurs as we did not pay attention to the question *"how a certain coalition is formed", but whether "is this coalition farsightedly stable"*. However, as farsighted stability is based on the inducement process we limit our attention to inducement process and not to the coalition building process. We focus on the coalition building process by presenting preferred farsightedly stable coalitions in the next section.

[11]There is no farsightedly-stable coalition that does not belong to $Coal_{all}$. This indicates that *every profitable coalition converges (by testing for farsighted stability) only to a coalition that is profitable too.* In this sense, *the set* $Coal_{all}$ *is closed.* As Observations 2.3.2, 2.3.3 make clear that there is no farsightedly stable coalition that at least one member of it has a lower profit than his atom-structure profit. One can imagine such a coalition. For example, we have a three member profitable coalition C_3. We suppose that after C_3 is formed, one certain country outside of the coalition has a very low profit (this happen rarely as *positive spillover* property is very frequently satisfied). Besides we further suppose that by joining the coalition this country can increase his profit, but it is still lower than his atom-structure behavior profit. If the forth-member coalition that is formed is farsightedly stable, we have a farsightedly stable coalition where a country has a lower profit than his atom-structure profit. As already noted above *the positive spillover property* prevents the above situations to occur.

to improve the welfare of these countries except by leaving the coalition or *by implementing a welfare transfer scheme.* Implementing a welfare transfer-scheme is not within the scope of this research which aims to find what coalition are stable in "selfish but farsighted world". As a consequence, it is natural that profitability condition is a border of "selfish but farsighted world", beyond this world the "farsighted and welfare-transferred world" begins which can possibly enable the existence of bigger stable coalitions. It is essential to note that the *asymmetry of countries* does not allow *large profitable coalitions.* When coalition members maximize their joint welfare the optimization process requires further emissions reductions in those countries where it is cheaper to decrease emissions (where marginal abatement cost is low) until profit maximization is reached and the marginal abatement costs of coalition members are equal. As a result, those countries which initially have a low marginal abatement cost (if difference in marginal abatement cost among coalition members is also large before coalition formation) *will probably not satisfy the profitability condition.* On the other hand, the benefits from pollution abatement vary for different countries. This implies that countries that benefit less from pollution abatement, *will probably not satisfy the profitability condition.* It follows that farsighted stability is a function of the asymmetry of countries. Free-riding does not allow large myopic stable coalitions and asymmetry of countries does not allow large farsightedly stable coalitions.

2.4 Preferred and dominated farsightedly stable coalitions

The farsighted stability concept can be improved by looking carefully at the inducement process. The inducement process means how much coalition-members can "see and change" in order to find the best coalition. Suppose we have a coalition structure (such as the atom structure) as a starting state that *cannot be induced* by two different farsightedly stable coalitions. The following question can be raised: *Which farsightedly stable coalition is most likely to be formed from this starting point ?* It is clear that the most usual starting point is the atom structure. We will compare the farsightedly stable coalitions not only with coalitions that originate from the general inducement process but also with the coalitions that originate from the most usual starting point, the atom structure. We can use this criterion in order to refine further our farsightedly stable coalitions.
The formal definition of *dominated coalition* is introduced below.

Definition 2.17 *A farsightedly stable coalition C_m is dominated if and only if:*

$$\forall \textit{ country } i \in C_m \quad \exists\, C_{k_i} \quad |\pi_{C_{k_i}}(i) > \pi_{C_m}(i) \textit{ and } C_{k_i} \textit{ is a not-dominated farsighted stable coalition}$$

$\pi_{C_{k_i}}(i)$, $\pi_{C_m}(i)$ *are profits of the country i as a member C_k and C_m.*

A coalition C_m is dominated if there are not-dominated farsightedly stable coalitions where every country member of C_m gets higher profit.

Definition 2.18 *A coalition C_m dominates C_n, $C_m \succ C_n$ if and only if:*

$$\forall \textit{ country } i \in C_m \cap C_n \quad \pi_{C_m}(i) > \pi_{C_n}(i) \textit{ and } C_m \textit{ is a not-dominated coalition}$$

$\pi_{C_m}(i)$, $\pi_{C_n}(i)$ *are profits of the country i as a member C_m and C_n.*

A coalition dominates another one if the country-members of first coalition get higher profit in comparison to the second one.

Definition 2.19 *A country i prefers C_m over C_n, $C_m \succ_i C_n$ if and only if:*

$$for \textit{ country } i \in C_m \quad \pi_{C_m}(i) > \pi_{C_n}(i)$$

$\pi_{C_m}(i)$, $\pi_{C_n}(i)$ *are profits of the country i as a member C_m and C_n.*

It simply means that a country prefers the coalition where it gets higher profit.

Definition 2.20 *A coalition C_m is preferred over C_n, $C_m \succeq C_n$ if and only if:*

$$for\ the\ majority\ of \textit{ country } i \in C_m \cap C_n\ \pi_{C_m}(i) > \pi_{C_n}(i) \textit{ and no coalition is preferred over } C_m$$

$\pi_{C_m}(i)$, $\pi_{C_n}(i)$ *are profits of the country i as a member C_m and C_n.*

A coalition C_m is preferred over C_n if the majority of their mutual countries gets higher profit in C_m. It is essential to note that if C_m is preferred to (or dominates) C_n then C_m cannot induce C_n or vice-versa (one can say *the inducement process* does not cover the *preference (dominance) relation*). Moreover, we see the dominance relation as a complement of the inducement process that somehow makes the inducement process complete. The coalitions that are more easily formed will be not only farsightedly stable but also preferred coalitions. Therefore, *the preferred (dominated) farsightedly stable coalitions* are more probably formed.
The definitions (5.8) and (4.12) help us also to answer the question which coalitions with a fixed number of the countries (two, three or more) are more likely to be formed.

Table 2.2: The three member profitable coalitions C^3_{pro} where the country-members C^3_{high} reach the highest profits

C^3_{pro}	C^3_{high}
(USA, SEA, CHI)	$USA,\ SEA,\ CHI$
(EEU, CAM, SAS)	$EEU,\ CAM,\ SAS$
(CAN, FSU, LAM)	$CAN,\ FSU$
(JPK, NAF, SSA)	JPK
(USA, LAM, CHI)	LAM
(USA, CHI, NAF)	NAF
(USA, CHI, SSA)	SSA
(EEU, SAS, SIS)	SIS

First we consider the three member coalition set and determine which coalition is most likely to form among these farsightedly stable (FS) coalitions ?
One concludes from the Table (2.2) that among these FS coalitions, the two coalitions $(3-12)$ and $(3-7)$ are more probable. The first column C^3_{pro} contains the profitable coalitions, and the second column, the countries that have the highest profit in the coalition on the left (although we are interested only in farsightedly stable coalitions, the profit comparison is done for all profitable coalitions). It shows that the first coalition $(3-12)$ $(EEU, CAM, SAS)^{fs}$ dominates any three member coalition with which it has mutual countries. Coalition $(3-7)$ $(CAN, FSU, LAM)^{fs}$ is preferred over any three member coalition with which it has mutual countries. [12].
The preferred four-member coalitions are $(4-8)$ $(CAN, EEU, CAM, SAS)^{fs}$ and $(4-6)$ $(USA, SEA, CHI, SSA)^{fs}$ (see Table (2.3)). Moreover, the first coalition dominates any four-member coalition with whom it has mutual countries.
From our calculations we find that the most preferred five member coalition are $(5-7)$ $(CAN, EEU, CAM, SAS, SIS)^{fs}$ and $(5-5)$ $(USA, SEA, CHI, NAF, SSA)^{fs}$. Table (2.4) displays that these coalitions are preferred over all five-member profitable coalitions. Moreover, the first coalition dominates any five-member profitable coalition with whom it has mutual countries.
Note that our six-member farsightedly stable coalition is preferred over all five member profitable coalitions except $(5-7)$.

[12] As there is no two-member farsightedly stable coalition no comparison is presented for them.

Table 2.3: The four member profitable coalitions C^4_{pro} where the country-members C^4_{high} reach the highest profits

C^4_{pro}	C^4_{high}
(CAN, EEU, CAM, SAS)	$CAN,\ EEU,\ CAM,\ SAS$
(USA, SEA, CHI, SSA)	$USA,\ SEA,\ SSA$
(USA, LAM, SEA, CHI)	$LAM,\ SEA$
(USA, CHI, NAF, SSA)	NAF

Table 2.4: The five member profitable coalitions C^5_{pro} where the country-members C^5_{high} reach the highest profits

C^5_{pro}	C^5_{high}
$(CAN, EEU, CAM, SAS, SIS)$	$CAN,\ EEU,\ CAM,\ SAS,\ SIS$
$(USA, SEA, CHI, NAF, SSA)$	$USA,\ SEA,\ NAF,\ SSA$
$(USA, LAM, SEA, CHI, SSA)$	$LAM,\ CHI$
$(CAN, JPK, LAM, SAS, SSA)$	JPK

We have numerically checked that coalitions $(6-1)$ $(USA, LAM, SEA, CHI, NAF, SSA)$ or $(5-7)$ $(CAN, EEU, CAM, SAS, SIS)$ are preferred to any other farsightedly stable coalition. Consequently the coalitions $(6-1)$ and $(5-7)$ are our preferred farsightedly stable coalitions.
Based on the discussion in the section four we can build possible "histories" of single coalition formation.
One possible "history" that involves the six members of farsightedly stable coalition $(USA, LAM, SEA, CHI, NAF, SSA)$ is:

$$(Atom_{Structure}) \Rightarrow (USA, CHI) \Rightarrow (USA, SEA, CHI) \Rightarrow (USA, SEA, CHI, SSA)^{fs} \Rightarrow$$
$$\Rightarrow (USA, SEA, CHI, NAF, SSA)^{fs} \Rightarrow (\textbf{ USA, LAM, SEA, CHI, NAF, SSA})^{fs}$$

A possible "history" is a "history" that leads *to a preferred (or dominated) farsightedly stable coalition.* All the coalitions between the atom structure and the final coalition are preferred coalitions.

2.4.1 Numerical comparison between different coalition structure

In order to compare the improvement in welfare and abatement levels of different coalition structure, we introduce some new notation:

$Pr_{atom}(i)$, $Abat_{atom}(i)$ are the profit and abatement of the country i in the atom structure.
$Pr_6(i)$, $Abat_6(i)$ are the profit and abatement of the country i when the coalition $(USA, LAM, SEA, CHI, NAF, SSA)$ (we call it the first coalition) with 6 members is formed.
$Pr_5(i)$, $Abat_5(i)$ are the profit and abatement of the country i when the coalition $(CAN, EEU, CAM, SAS, SIS)$ (we call it the second coalition) with 5 members is formed.

$(Pr_6(i) - Pr_{atom}(i))/Pr_{atom}(i)$, $(Abat_6(i) - Abat_{atom}(i))/Abat_{atom}(i)$ are the fraction of profit and abatement change of the country i (in relation to atom structure) when the 6 members coalition is formed.
$(Pr_5(i) - Pr_{atom}(i))/Pr_{atom}(i)$, $(Abat_5(i) - Abat_{atom}(i))/Abat_{atom}(i)$ are the fraction of profit and abatement change of the country i (in relation to atom structure) when the 5 members coalition is formed.

We present the fraction of profit change of each country when the first coalition is formed in Figure

(2.1)[13]. The greater profit improvements are taking place in non-signatories[14] (as expected). The fraction of abatement change of each country when the six member coalition is formed, is shown in Figure (2.2). As the cost functions are independent of one another (no carbon leakage too), then only the coalition members reduce their emissions, and moreover they reduce strongly.
The fractional profit change of each country when the second coalition is formed, is presented in Figure (2.3). As before, the bigger profit improvements take place in non-signatories, but the profit improvements are significantly smaller in comparison to the first coalition. The first coalition brings a total profit improvement that is 22.2 times higher in comparison to the second coalition. This occurs because in the atom structure the profits of the first coalition members are usually significantly higher than those of the second coalition members, see Figure (2.11). Figure (2.4) displays the fractional abatement change of each country when the second coalition is formed. The coalition members achieve significant emissions reductions (in fractional terms) but these reductions are considerably smaller in absolute terms than those achieved by members of the first coalition. The first coalition realizes a total abatement level that is 14.3 times higher than that of the second coalition and this takes place again because in the atom structure the abatement levels of members of the first coalition are usually significantly higher than those of the members of the second coalition, see Figure (2.12).
Thus farsighted stability produces better results in terms of welfare and abatement levels compare to D'Aspremont stability[15].

2.5 Multiple farsightedly stable coalitions

In this section, the discussion is extended to the question of multiple farsightedly stable coalitions by considering coalitions (6-1) and (5-7) simultaneously. Note that the costs of emission reduction of a region are independent of the abatement of other regions and the benefits are linear. As a consequence in case of multiple coalitions the changes in the pay-off of each region is independent of the behavior of other regions provided that*the two coalitions do not exchange members*. It follows that our coalitions are farsightedly stable if there is no inducement process which results in switching members between two coalitions. This has been numerically verified. Thus we conclude that our coalitions are farsightedly stable[16]. Therefore, we have two preferred farsightedly stable coalitions (the preference relation can be applied the same as in the case of single coalitions) that coexist which are:

$(6-1)^{fs} \qquad (USA, LAM, SEA, CHI, NAF, SSA),$

$(5-7)^{fs} \qquad (CAN, EEU, CAM, SAS, SIS)$

In Figures (2.5) and (2.6) the fractional profit and abatement change of each country is presented when the two above coalitions are formed. Almost 96% of the total profit improvement and 93% of the total abatement improvement is due to the first coalition with six members, see Figure (2.7)and Figure (2.8). The second coalition alone improves the average abatement levels by 18% and the average profit by 3.4% compared to the atom structure.
So, there are 11 regions out of 16 (approximately two thirds of countries) that can cooperate, and they

[13]Please note that the Figures (2.9), (2.10), (2.11), (2.12) are in Appendix 9.
[14]The countries that do not take part in any coalition are called non-signatories.
[15]The D'Aspremont stable coalition that brings the highest improvement in welfare and abatement levels is (USA, CHI, NAF). This is a sub-coalition of the farsightedly stable coalition $(USA, CHI, NAF, SSA, SEA, LAM)$. The six member farsighted stable coalition $(USA, LAM, SEA, CHI, NAF, SSA)$ improves the welfare and abatement by 27 % and 97 % respectively in comparison to D'Aspremont stable coalition (USA, CHI, NAF). The largest D'Aspremont stable coalition is $(CAN, JPK, EEU, CAM, LAM, NAF, SIS)$.
[16]Only one inducement process is still not considered, that is the division of a coalition in two (or more) sub-coalitions. Suppose that a coalition with six countries is divided into two sub-coalitions with three countries (without loss of generality). Country members maximize their total profit in all coalitions. Suppose that maximum value found for the large coalition is $Prof_1$ and for two sub-coalitions are $Prof_a$ and $Prof_b$ (it is clear that those maximum points are reached for different values of abatement levels R). Note that $Prof_1$ is an unique maximum because the Hessian matrix is negative definite, so we have a strict concave function. As a consequence $Prof_1 > Prof_a + Prof_b$, otherwise it contradicts the fact that $Prof_1$ is unique. This implies that at least one country has reduced profit (when the coalition is divided) so that the inducement process is not possible.

improve the abatement level by around 4 times and profit by around 2 times in comparison to the atom structure. This is an interesting result, as well one of the few optimistic ones from non-cooperative game theory. This result is a consequence of using a complex stability concept like farsightedly stability. However, the grand coalitions can still do far better than our two coalitions. The grand coalition can further improve the total profit more than 2 times and the total abatement level by almost 4 times in comparison to our two coalitions, see Figure (2.7)and Figure (2.8), and hence there is still much room for improvement that cannot be exploited due to the selfishness of our players (countries).
Other interesting results that oppose some previous conclusions of scientific literature (Osmani & Tol (2006), Asheim, B.G et. al. (2006)) is that multiple coalitions can do better than single ones in global pollution problems. We consider the FUND model more realistic than the above referenced papers. We reinforce the conclusion that the cooperation of certain countries like USA or China (all countries of first coalition) is crucial for a successful international environmental policy. This means that it is not only essential that a large number of countries signs an IEA but also that certain key countries must do so. Surprisingly the West European Union (WEU) is not participant of any coalition and this contradicts reality. This may occur because we are not considering any *commitment to cooperation (of our 16 world regions)* in our non- cooperative game theoretic approach[17].
Farsighted stable coalitions generate better results in terms of welfare and abatement levels compare to D'Aspremont stable coalitions[18].

2.6 Conclusions

This paper examines the problem of deriving the size of farsightedly stable IEAs. The FUND model provides the cost-benefit function of pollution abatement. It is clear that the dynamic of damage-cost functions of the FUND model determines the results.
The D'Aspremont stability concept, which assumes that the players are myopic and consider only single-player movements, is very restrictive. Instead, the farsightedly stability concept is used. Farsighted stability implies that if a country considers deviating, it will realize that a deviation may trigger further deviations, which can worsen the country's initial position. All farsightedly stable coalitions are found by using simple combinatorial algorithms. As it is usually true (for FUND model is always true) that farsightedly stable coalitions must be profitable, a significant reduction of computational effort is achieved. We refine and improve further the farsighted stability concept to preferred farsighted stability. Preferred farsightedly stable coalitions can more likely form from a usual starting state, such as the atom structure, in comparison to other farsightedly stable coalitions.
The D'Aspremont stability and farsighted stability concepts, surprisingly seem to reach one similar conclusion, namely that the size of a single stable coalition is relatively small. D'Aspremont stability argues that the free-riding makes it difficult to have large single stable coalitions. In contrast, with farsighted stability, coalition size is limited by the constraint that a coalition must be profitable. In addition, the asymmetry of countries makes the profitability condition difficult to fulfil and prevents large farsightedly stable coalitions. Nevertheless, single farsightedly stable coalitions clearly improve the welfare and abatement level in comparison to D'Apremont stable coalitions.
We consider also multiple farsightedly stable coalitions, which leads to an optimistic result. Almost 70 % of all regions can cooperate and improve welfare and environmental quality significantly. We show that multiple farsighted coalitions have a clear advantage compared to multiple D'Apremont stable coalitions. As our approach considers only economic incentives, it will be interesting to include other factors like commitment to cooperation or technology as well as more detailed regions and cooperative game theory.

[17] On the contrary, in a cooperative approach WEU is a key player, but the cooperative attitude is out of scope of our paper. WEU is always a member of coalitions (CHI, FSU and USA too) that bring the maximum welfare improvement, although they are not stable.

[18] We have calculated the preferred D'Apremont stable coalitions which are (USA, CHI, NAF), (ANZ, SAS) and (FSU, LAM). Nevertheless, only the six member farsighted stable coalition $(USA, LAM, SEA, CHI, NAF, SSA)$ improves the welfare and abatement by 20 % and 79 % in comparison to all *three preferred D'Apremont stable coalitions* together.

Acknowledgment

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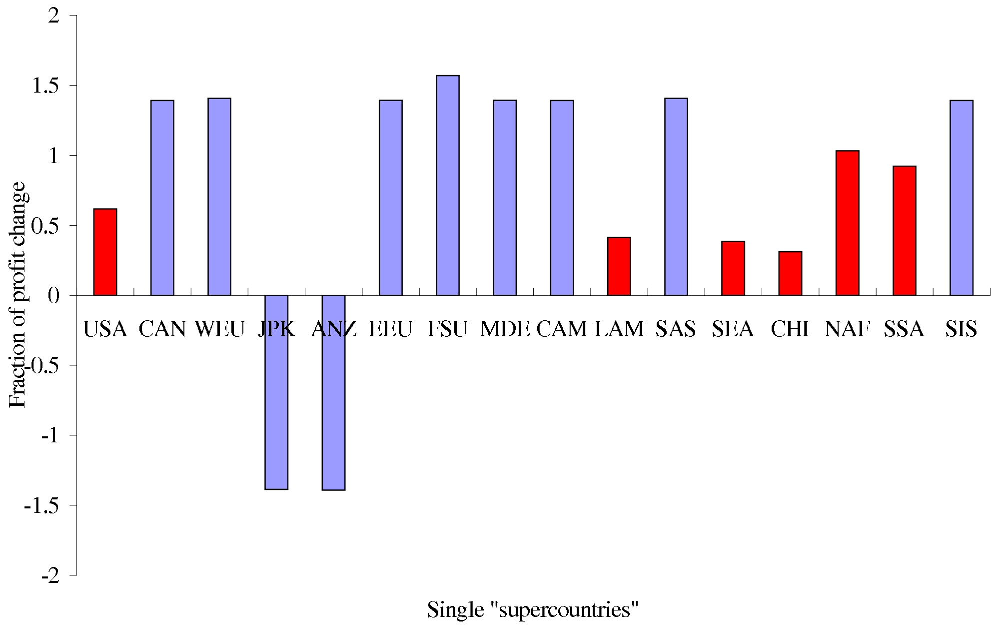

Figure 2.1: Fraction of profit change when the first coalition is formed, red color → first coalition, violet color → nonsignatories

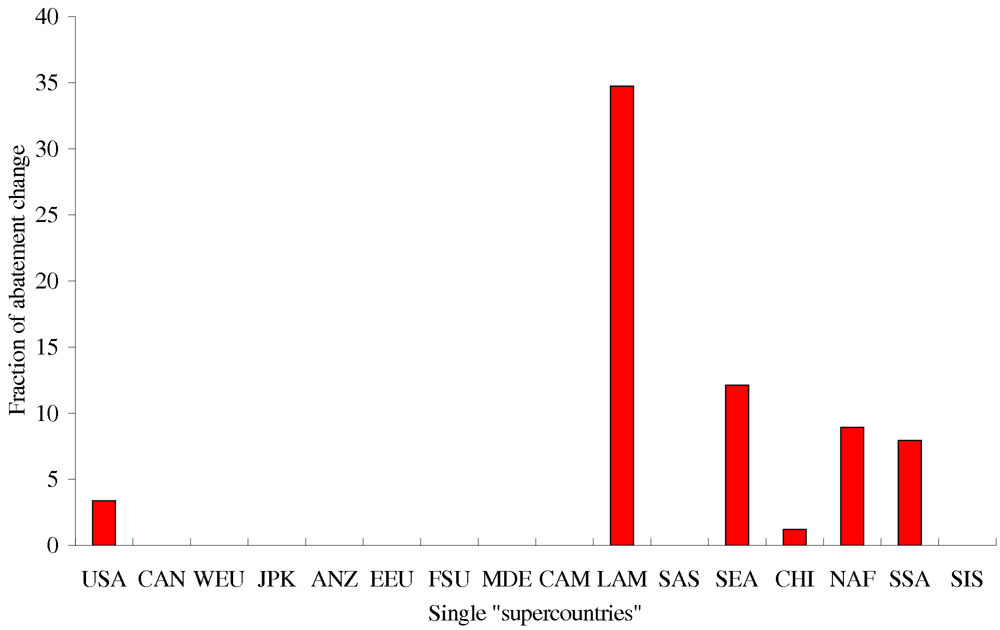

Figure 2.2: Fraction of abatement change when the first coalition is formed, red color → first coalition

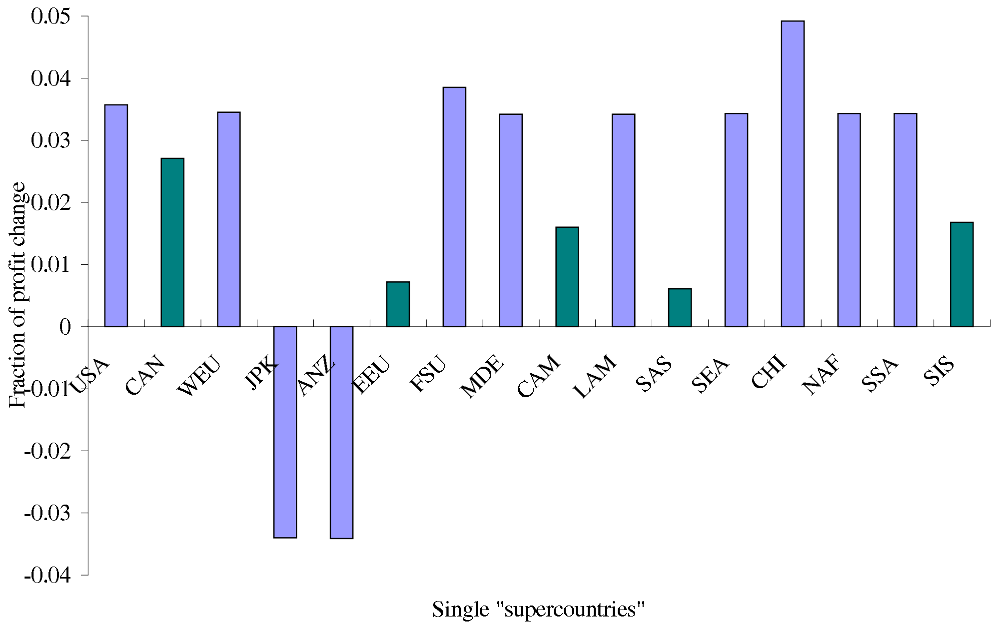

Figure 2.3: Fraction of profit change when the second coalition is formed, green color → second coalition, violet color → nonsignatories

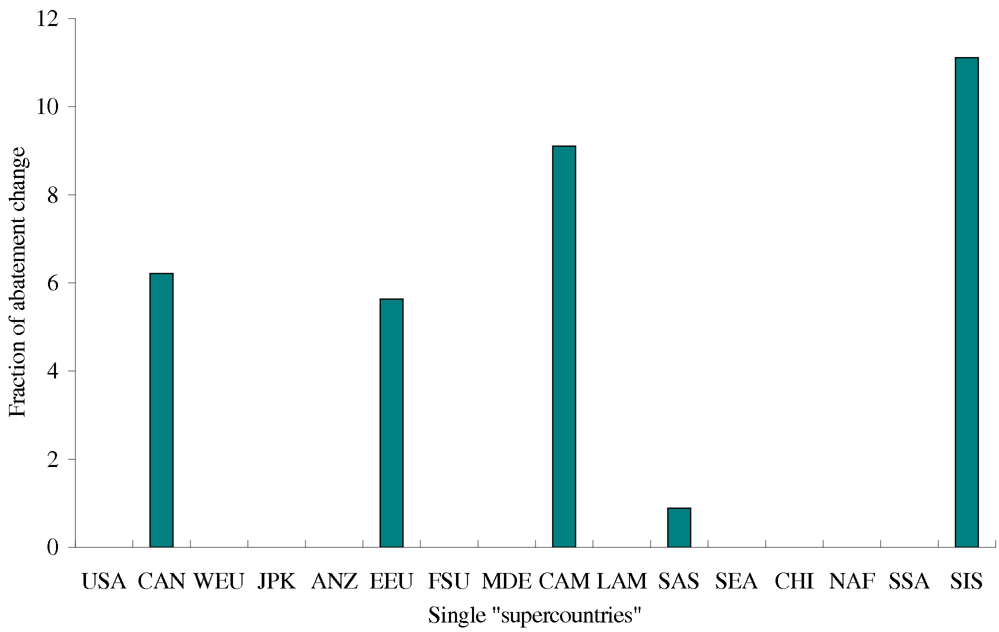

Figure 2.4: Fraction of abatement change when the second coalition is formed, green color → second coalition

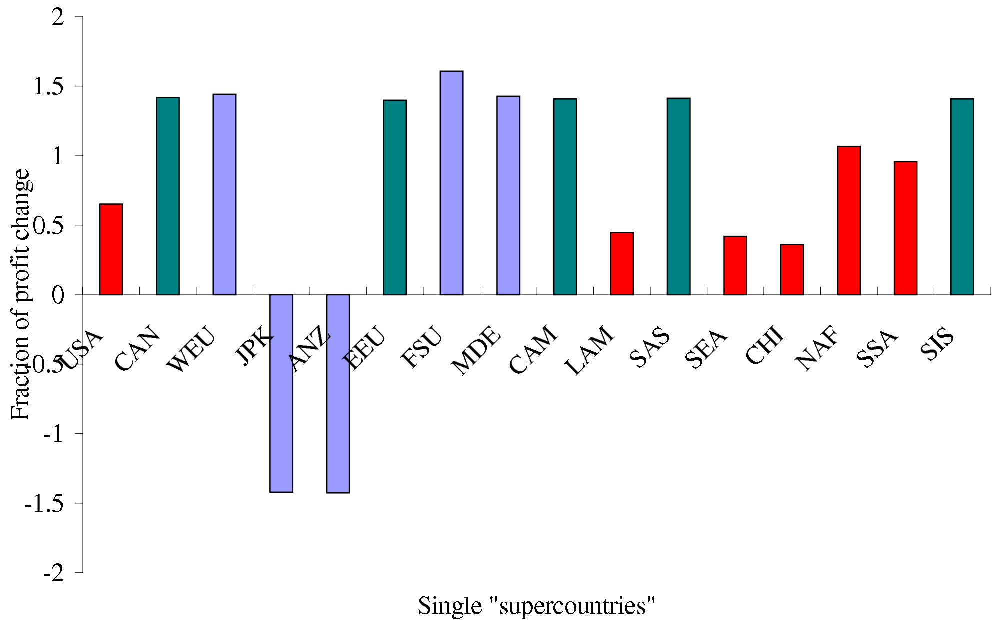

Figure 2.5: Fraction of profit change when both coalitions are formed, red color → first coalition, green color → second coalition, violet color → nonsignatories

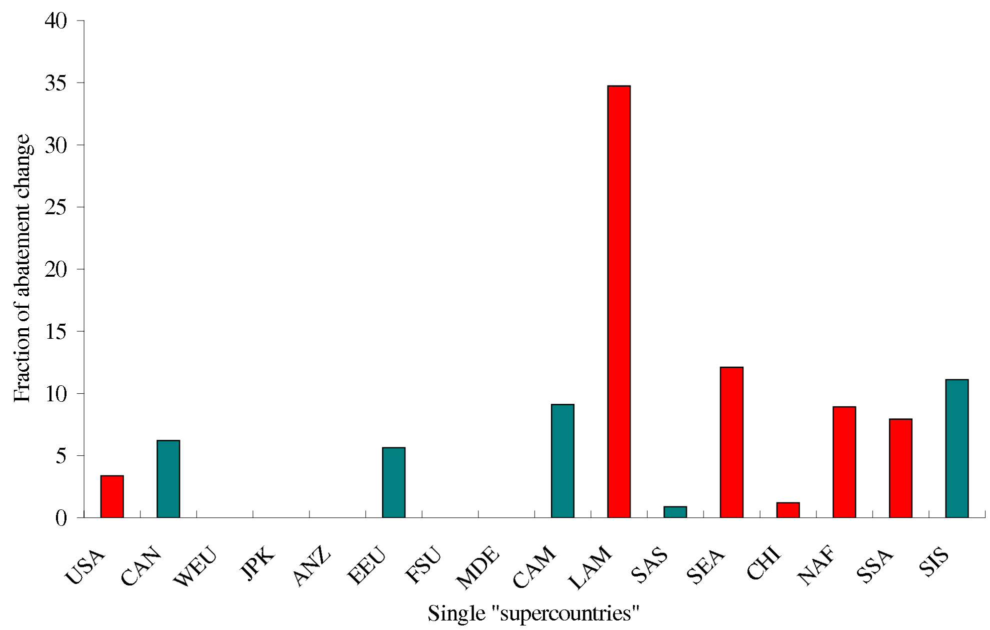

Figure 2.6: Fraction of abatement change when both coalitions are formed, red color → first coalition, green color → second coalition

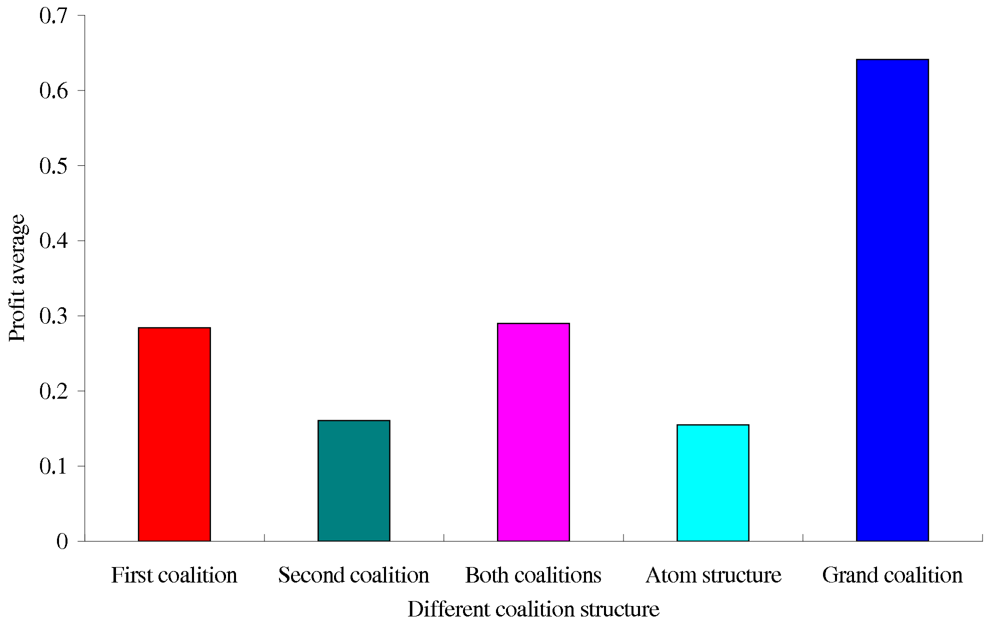

Figure 2.7: Average profit levels of different coalition structure

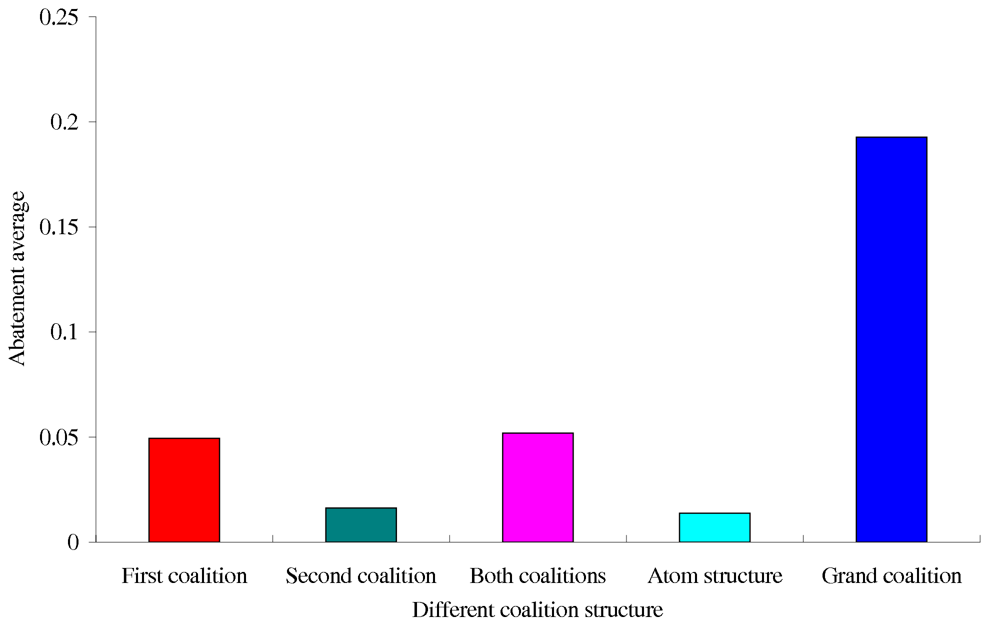

Figure 2.8: Average abatement levels of different coalition structure

2.7 Appendix

2.7.1 Simple algorithms for finding single farsightedly-stable coalitions

Here the algorithms for finding farsightedly stable coalitions are presented. The first algorithm is described in Table (2.5). It tests a coalition *for external farsighted stability* (EFS, see definition (5.4)). Suppose we would like to check coalition $C_n \equiv (1, 2 \ldots n)$ for EFS.

Table 2.5: Algorithm for finding externally farsightedly stable (EFS) coalitions

Take the coalition $C_n \equiv (1, 2 \ldots n)$ where $n < 16$.
Calculate $\pi_1(1)...\pi_1(16)$, the profit of this coalition structure.
for i=(n+1) to 16
(the loop does not contain countries *1,2* ... and n)
Find all coalitions with i-elements $i \geq (n+1)$ where n elements are always $(1, 2 \ldots n)$.
take a coalition with i countries
Calculate $\pi_2(1)...\pi_2(16)$, the profit of this coalition structure.
if $[\pi_2(1) > \pi_1(1) \wedge \pi_2(2) > \pi_1(2) \wedge \ \ldots \ \wedge \pi_2(i) > \pi_1(i)]$ (main condition)
the coalition $(1, 2 \ldots n)$ is not externally farsightedly stable (EFS).
endif
end
If the main condition is never satisfied for i=(n+1) to 16, then
the coalition $(1, 2 \ldots n)$ is externally farsightedly stable.

If the algorithm of Table (2.5) finds a $\boldsymbol{i}$ member-coalition C_i for which *the main condition* $[\pi_2(1) > \pi_1(1) \wedge \pi_2(2) > \pi_1(2) \wedge \ \ldots \ \wedge \pi_2(i-1) > \pi_1(i-1) \wedge \pi_2(i) > \pi_1(i)]$ holds, then our initial coalition C_n is not externally farsightedly stable. *But if the main condition is never satisfied (for i=(n+1) to 16), then we say that no external inducement is possible.* If no external inducement is possible, then the coalition (C_n in our case) is *externally farsightedly stable (EFS).*
The algorithm for internal farsightedly stability will be presented below. Suppose again, that we have a coalition with $\boldsymbol{n}$ countries $C_n \equiv (1, 2 \ldots n)$. We need to find every sub-coalition (of 2 countries, 3 countries ... and (n-1) countries). We name by $\pi^{'}(1)...\pi^{'}(16)$ the profits when the sub-coalitions are formed, and $\pi(1)...\pi(i1)...\pi(i5)...\pi(16)$ the profits when only the n member coalition C_n is formed. Then if *the below condition* is satisfied (for any sub-coalition of C_n with i members where i=2 to (n-1)): $[\pi^{'}(1) > \pi(1) \wedge \pi^{'}(2) > \pi(2) \wedge \pi^{'}(i-1) > \pi(i-1) \wedge \pi^{'}(i) > \pi(i)]$, we say that an internal inducement is possible. If an internal inducement is possible than the coalition *is not internally farsightedly stable (IFS).* All steps in this algorithm are presented in Table (2.6).

Testing *sub-coalition stability* of coalition C is similar to testing every *sub-coalition of coalition C for external farsighted stability.*

2.7.2 Numerical results for three-member coalitions

In this subsection we present a small part of the numerical computations which test and find the three-member coalitions that are not farsightedly stable. Firstly, we note that all profitable coalitions are internally farsightedly stable (including the three-member coalitions). Three-member coalitions which are not externally farsightedly stable are presented in Tables 2.7, 2.8 and 2.9. The first column of Table 2.7 presents the members of five-member final coalitions. The three countries of the coalition that are inspected are labeled in bold letters, while the members that join the initial coalition are in normal typeface. The second column of Table 2.7, Pr_3, displays the profits (in billions of dollars) of the final coalition members when only the three-member coalition exists, while the third column Pr_5 shows the profits of final coalition members when only the five-member coalition exists. The profits of each country are higher when the five-member coalition is formed (Pr_5) in comparison to the profits when the

Table 2.6: Algorithm for finding internally farsightedly stable (EFS) coalitions

Take the coalition $C_n \equiv (1, 2 \ldots n)$ where $n \leq 16$.
Calculate $\pi(1)..\pi(i1)..\pi(i5)..\pi(16)$ the profits of this coalition structure.
for i=2 to (n-1) (find all sub-coalition with i elements from coalition $(1, 2 \ldots n)$)
Take a sub-coalition with i elements.
Calculate $\pi^{'}(1)..\pi^{'}(i1)..\pi^{'}(i5)..\pi^{'}(16)$ the profits of this coalition structure.
if $[\pi^{'}(1) > \pi(1) \wedge \pi^{'}(2) > \pi(2) \wedge \pi^{'}(i-1) > \pi(i-1) \wedge \pi^{'}(i) > \pi(i)]$ (main condition)
the coalition $(1, 2 \ldots n)$ is not an internally farsightedly stable coalition
endif
end
If the main condition is never satisfied for i=2 to (n-1), then
the coalition $(1, 2 \ldots n)$ is internally farsightedly stable.

three-member coalition is formed (Pr_3). As a result, the three member coalition (USA,LAM,CHI) is not externally farsightedly stable. Columns four, five and six of Table 2.7 are similar to columns one, two and three,and Tables 2.8 and 2.9 are similar to Table 2.7. Tables 2.10 and 2.11 introduce the three-member coalitions which are not sub-coalition farsightedly stable. In the first column, the country members which change their position (join or leave the initial coalition) are placed. The three countries of a primary coalition which is inspected are labeled in bold letters, while the three members of the final coalition are marked with an asterisk in the top-right. It is clear that countries in bold letters and have a asterisk in top-right are simultaneously members of a primary and of the final coalition. The second column of Table 2.7, Pr_{3old} presents the profits of final coalition members when only the primary three-member coalition is formed, while the third column of Table 2.7, Pr_{3new} introduces the profits when the final three-member coalition is built. The profits of members of final three-member coalition (*with a asterisk in the top-right*) are greater when the final three-member coalition is formed Pr_{3new} compared to the primary three-member coalition Pr_{3old}. It follows that the three member coalition (JPK,NAF,SSA) is not sub-coalition farsightedly stable. Finally, Table 2.11 is similar to Table 2.10.

Table 2.7: Three member coalitions which are not externally farsightedly stable.

Coalition	Pr_3	Pr_5	*Coalition*	Pr_3	Pr_5
USA	0.5336	0.5336	**USA**	0.5765	0.6916
LAM	0.0614	0.0614	**SEA**	0.177	0.2057
CHI	0.7613	0.7613	**CHI**	0.8048	0.817
NAF	0.322	0.322	NAF	0.3533	0.3976
SSA	0.3573	0.3573	SSA	0.3921	0.4173

Table 2.8: Three member coalitions which are not externally farsightedly stable.

Coalition	Pr_3	Pr_5	*Coalition*	Pr_3	Pr_5
USA	0.457	0.6916	**CAN**	0.0198	0.0204
SEA	0.177	0.2057	EEU	0.0216	0.0217
CHI	0.7766	0.817	**CAM**	0.0142	0.0144
NAF	0.2203	0.3976	SAS	0.075	0.0753
SSA	0.2398	0.4173	**SIS**	0.0118	0.012

Table 2.9: Three member coalition which is not externally farsightedly stable.

Coalition	Pr_3	Pr_5
CAN	0.0199	0.0204
EEU	0.0216	0.0217
CAM	0.0142	0.0144
SAS	0.0751	0.0753
SIS	0.0118	0.012

Table 2.10: Three member coalition which is not sub-coalition farsightedly stable.

Coalition	Pr_{3old}	Pr_{3new}
USA^*	0.4476	0.457
JPK	-0.3032	-0.3467
NAF*	0.2057	0.2203
SSA*	0.2285	0.2398

Table 2.11: Three member coalition which is not sub-coalition farsightedly stable.

Coalition	Pr_{3old}	Pr_{3new}
USA^*	0.4824	0.5336
CAN	0.0205	0.0311
FSU	0.241	0.3945
LAM*	0.0599	0.0614
CHI^*	0.7149	0.7613

2.8 Appendix

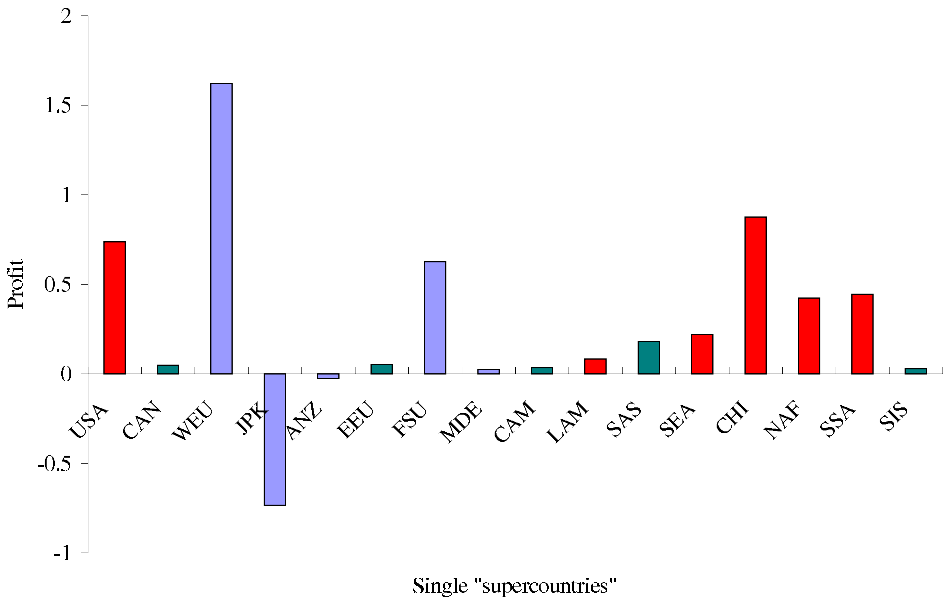

Figure 2.9: Profit levels when both coalitions are formed, red color → first coalition, green color → second coalition, violet color → nonsignatories

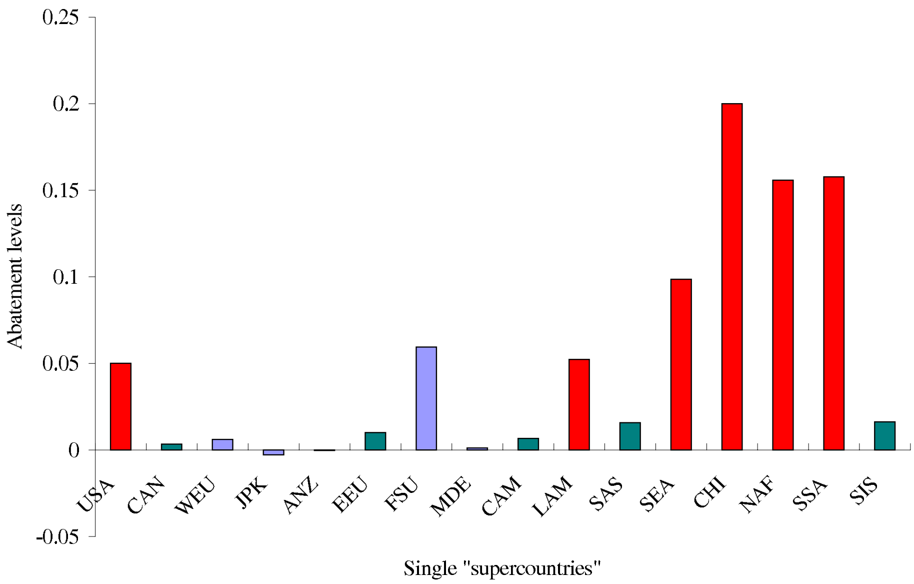

Figure 2.10: Abatement levels when both coalitions are formed, red color → first coalition, green color → second coalition, violet color → nonsignatories

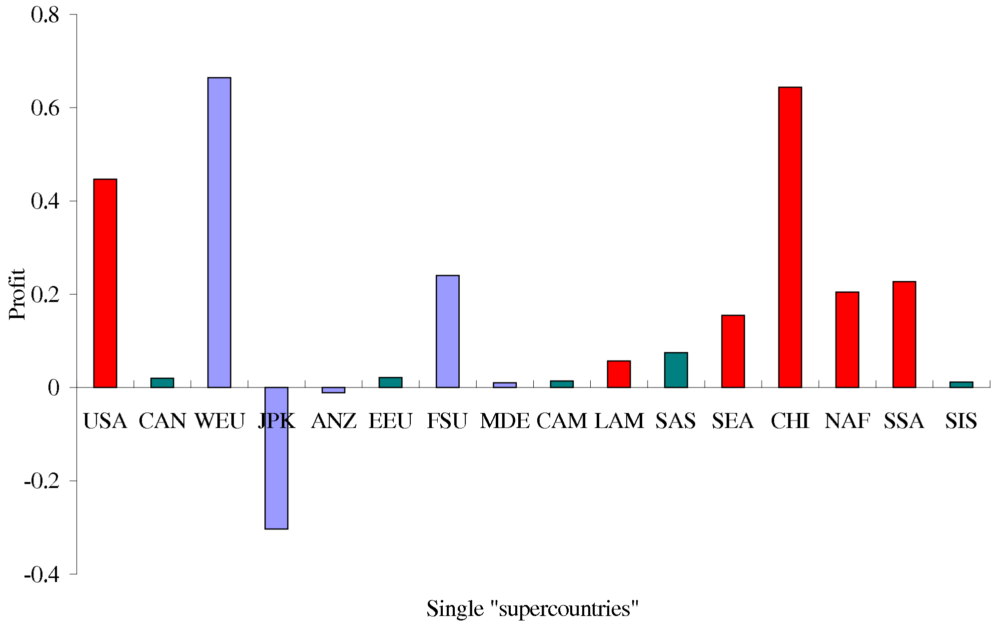

Figure 2.11: Profit levels in atom structure, red color → first coalition, green color → second coalition, violet color → nonsignatories

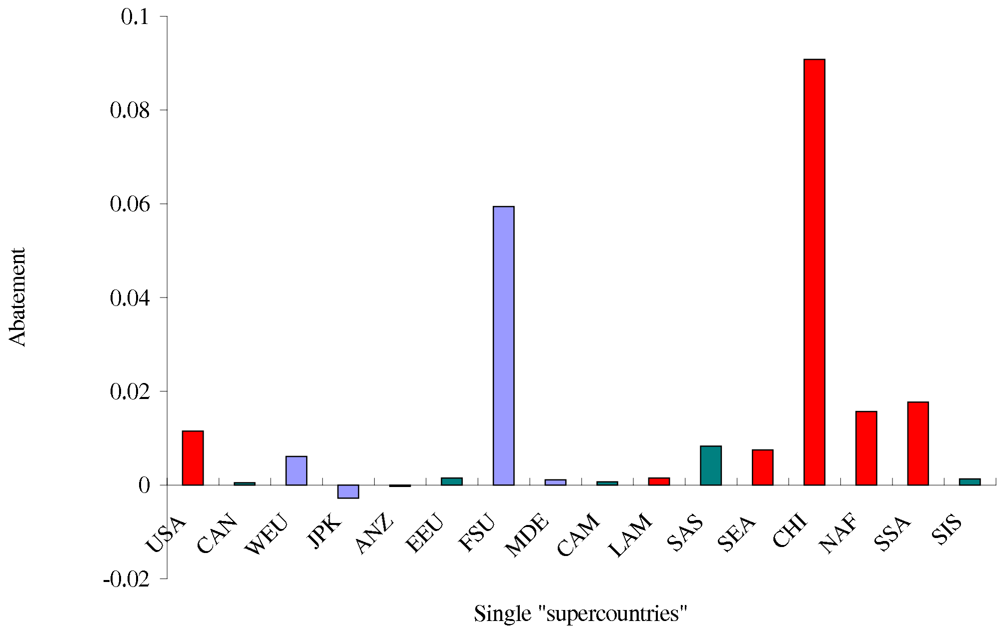

Figure 2.12: Abatement levels in atom structure, red color → first coalition, green color → second coalition, violet color → nonsignatories

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Chapter 3

From D'Aspremont to Farsightedly Stable International Environmental Agreements or what should we expect from Game Theory without Side Payments

From D'Aspremont to Farsightedly Stable International Environmental Agreements or what should we expect from Game Theory without Side Payments

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Abstract

We investigate the stability of International Environmental Agreements (IEA) by applying game theory. The paper extends further our previous research on farsightedly stable coalitions and preferred farsightedly stable coalitions (Osmani & Tol 2009). The integrated assessment model FUND provides the cost-benefit payoff functions of pollution abatement for sixteen different world regions. The stability concept of D'Aspremont et al. (1983) and farsighted stability of Chwe (1994) are compared. D'Aspremont stability assumes that players are myopic while farsighted stability assumes perfect foresight of the players and predicts which coalitions can be formed when players are farsighted. The D'Aspremont stable coalitions are frequently subsets of farsightedly stable coalitions. Furthermore, farsightedly stable coalitions can be frequently the largest size stable coalition, that game theory without side payments can reach. Additionally, they bring always the biggest improvement in environmental and welfare. All farsightedly stable and D'Aspremont stable coalitions are found and their improvement to environment and welfare are computed.

Keywords: coalition formation, game theory, farsighted stability, D'Aspremont stability, integrated assessment modeling.

JEL: C02, C72, H41

3.1 Introduction

The body of literature on International Environmental Agreements (IEA) has two conflicting views. One is based on cooperative game theory and concludes that the grand coalition is stable by using the core concept and implementing transfers to solve the heterogeneity of the countries involved (Chander & Tulkens 1997, Chander & Tulkens 2006, Eyckmans & Tulkens 2003, Chander 2007). The other view is rooted in the non-cooperative game theory and became the dominant path in the literature (Barrett 1994, Barrett 2003, Botteon & Carraro 2001, Osmani & Tol 2005, Finus & Ierland & Dellnik 2006, Rubio & Ulph 2006, McGinty 2007).
The usual approach of non-cooperative game theory to stable IEAs is based on the idea developed for cartel stability (D'Aspremont et al. (1983)) and requires so-called internal and external stability. Internal stability means that a country does not have an incentive to leave the coalition, while external stability

means that a country does not have an incentive to join the coalition. This part of the literature reaches the conclusion that the size of a stable coalition is typically very small.
This research develops further our previous work (Osmani & Tol 2009) on farsighted stability. Farsighted stability developed further the notation of stable sets of von Neumann & Morgenstern (1947). Stable sets are defined to be self-consistent. The notion is characterized by internal and external stability. Internal stability guarantees that the solution set is free from inner contradictions, that is, any two outcomes in the solution set cannot dominate each other and external stability guarantees that every outcome excluded from the solution is accounted for, that is, it is dominated by some outcome inside the solution. Harsanyi (1974) criticizes the von Neumann and Morgenstern solution also for its failing to incorporate foresight. He introduced the concept of indirect dominance to capture foresight. An outcome indirectly dominates another, if there exists a sequence of outcomes starting from the dominated outcome and leading to the dominating one, and at each stage of the sequence the group of players required to enact the inducement prefers the final outcome to its status quo. His criticism inspired a series of works on abstract environments including among others those of Chwe (1994), Mariotti (1997) and Xue (1998). Chwe (1994) introduces the notation of farsighted stability which is applied to the problem of IEAs by Diamantoudi & Sartzetakis (2002) and by Eyckmans (2003). Diamantoudi & Sartzetakis (2002) consider identical countries while asymmetric countries are taken into account in our model. Eyckmans (2003) studies only single farsightedly stable coalitions while we allow multiple farsightedly stable coalitions. In addition, a more systematic way of finding farsightedly stable coalitions is introduced in our approach[1] (as we have 16 different world regions, Eyckmans consider only 5 world regions).
The welfare functions of sixteen world regions are taken from the Climate Framework for Uncertainty, Negotiation and Distribution model FUND (see Section 4.2).
We extent the farsighted stability concept to preferred farsighted stability. The preferred farsightedly stable coalition is a farsightedly stable coalition where the majority of country members reach higher profits in comparison to any other farsightedly stable coalition[2]. The main contribution of the paper is a detailed discussion and comparison of D'Aspremont stability and farsighted stability. We show that the D'Aspremont stable coalitions are often sub-coalitions of farsightedly stable coalitions. Besides, farsightedly stable coalitions can be frequently the largest size stable coalition that game theory without side payments can realize. Moreover, they create always the biggest improvement in environmental and welfare.
Similarly to preferred farsightedly stable coalitions, we introduce preferred D'Aspremont stable coalitions. All D'Aspremont stable coalitions are found and multiple D'Aspremont coalitions are compared with multiple farsighted ones.
In section one the FUND model is introduced while in next section our game-theoretic model is presented. We go on in third section with a discussion on single D'Aspremont stable coalitions. In section four the preferred stable (farsighted and D'Aspremont stable) coalitions are taken into account. In the following section multiple stable coalitions are presented. In section six a conceptual and numerical comparison between D'Aspremont stable and farsightedly stable coalitions is performed. Section seven concludes.

3.2 FUND model

This paper uses version 2.8 of the Climate Framework for Uncertainty, Negotiation and Distribution (FUND). Version 2.8 of FUND corresponds to version 1.6, described and applied by Tol (1999a,b, 2001, 2002c), except for the impact module, which is described by Tol (2002a,b) and updated by Link and Tol (2004). A further difference is that the current version of the model distinguishes 16 instead of 9 regions. Finally, the model considers emission reduction of methane and nitrous oxide as well as carbon dioxide, as described by Tol (2006).
Essentially, FUND consists of a set of exogenous scenarios and endogenous perturbations. The model distinguishes 16 major regions of the world, viz. the United States of America (USA), Canada (CAN), Western Europe (WEU), Japan and South Korea (JPK), Australia and New Zealand (ANZ), Central and Eastern Europe (EEU), the former Soviet Union (FSU), the Middle East (MDE), Central America (CAM), South America (LAM), South Asia (SAS), Southeast Asia (SEA), China (CHI), North Africa (NAF), Sub-Saharan Africa (SSA), and Small Island States (SIS). The model runs from 1950 to 2300 in time steps of one year. The prime reason for starting in 1950 is to initialize the climate change impact module. In FUND, the impacts of climate change are assumed to depend on the impact of the previous

[1] Originating from Osmani & Tol, 2009
[2] We consider only *economic incentives* that a region has to join a coalition for environmental protection. Other factors like commitment to cooperation are not taken into account.

year, this way reflecting the process of adjustment to climate change. Because the initial values to be used for the year 1950 cannot be approximated very well, both physical and monetized impacts of climate change tend to be misrepresented in the first few decades of the model runs. The period of 1950-1990 is used for the calibration of the model, which is based on the IMAGE 100-year database (Batjes, Goldewijk, 1994). The period 1990-2000 is based on observations (WRI, 2000). The climate scenarios for the period 2010-2100 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett et al., 1992). The 2000-2010 period is interpolated from the immediate past, and the period 2100-2300 extrapolated.
The scenarios are defined by the rates of population growth, economic growth, autonomous energy efficiency improvements as well as the rate of decarbonization of the energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from land use change, methane and nitrous oxide. The scenarios of economic and population growth are perturbed by the impact of climatic change. Population decreases with increasing climate change related deaths that result from changes in heat stress, cold stress,malaria, and tropical cyclones. Heat and cold stress are assumed to have an effect only on the elderly, non-reproductive population. In contrast, the other sources of mortality also affect the number of births. Heat stress only affects the urban population. The share of the urban population among the total population is based on the World Resources Databases (WRI, 2000). It is extrapolated based on the statistical relationship between urbanization and per-capita income, which are estimated from a cross-section of countries in 1995. Climate-induced migration between the regions of the world also causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.
The market impacts are dead-weight losses to the economy. Consumption and investment are reduced without changing the savings rate. As a result, climate change reduces long-term economic growth, although consumption is particularly affected in the short-term. Economic growth is also reduced by carbon dioxide abatement measures. The energy intensity of the economy and the carbon intensity of the energy supply autonomously decrease over time. This process can be accelerated by abatement policies, an option not considered in this paper.
The endogenous parts of FUND consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, the impact of carbon dioxide emission reductions on the economy and on emissions, and the impact of the damages to the economy and the population caused by climate change. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is represented by the five-box model of Maier-Reimer and Hasselmann (1987). Its parameters are taken from Hammitt et al. (1992). The model also contains sulphur emissions (Tol, forthcoming[a]).
The radiative forcing of carbon dioxide, methane, nitrous oxide and sulphur aerosols is determined based on Shine et al. (1990). The global mean temperature T is governed by a geometric build-up to its equilibrium (determined by the radiative forcing RF), with a half-life of 50 years. In the base case, the global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents. Regional temperature follows from multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs (Mendelsohn et al., 2000). The global mean sea level is also geometric, with its equilibrium level determined by the temperature and a half-life of 50 years. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario of Kattenberg et al. (1996).
The climate impact module, based on Tol (2002b,c) includes the following categories: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems. Climate change related damages can be attributed to either the rate of change (benchmarked at 0.04°C) or the level of change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (cf. Tol, 2002c). People can die prematurely due to temperature stress or vector-borne diseases, or they can migrate because of sea level rise. Like all impacts of climate change, these effects are monetized. The value of a statistical life is set to be 200 times the annual per capita income. The resulting value of a statistical life lies in the middle of the observed range of values in the literature (cf. Cline, 1992). The value of emigration is set to be 3 times the per capita income (Tol, 1995, 1996), the value of immigration is 40 per cent of the per capita income in the host region (Cline, 1992). Losses of dryland and wetlands due to sea level rise are modelled explicitly. The monetary value of a loss of one square kilometre of dryland was on average $4 million in OECD countries in 1990 (cf. Fankhauser, 1994). Dryland value is assumed to be proportional to GDP per square kilometre. Wetland losses are valued at $2 million per square kilometre on average in the OECD in 1990 (cf. Fankhauser,

1994). The wetland value is assumed to have logistic relation to per capita income. Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.
Other impact categories, such as agriculture, forestry, energy, water, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their 'natural' units (cf. Tol, 2002b). Impacts of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, which is determined by a variety of factors, including plant physiology and the behaviour of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative (cf. Tol, 2002c). The impacts of climate change on coastal zones, forestry, unmanaged ecosystems, water resources, diarrhoea malaria, dengue fever, and schistosomiasis are modelled as simple power functions. Impacts are either negative or positive, and they do not change sign (cf. Tol, 2002c). Vulnerability to climate change changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth), heat-related disorders (with urbanization), and ecosystems and health (with higher per capita incomes). Other systems are projected to become less vulnerable, such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) (cf. Tol, 2002c).
Note that we make use of data only for the year 2005. This is sufficient as static game theory is used but with a sophisticated stability concept.

Table 3.1: Our data from year 2005, α abatement cost parameter (unitless), β marginal damage costs of carbon dioxide emissions (in dollars per tonne of carbon) E carbon dioxide emissions (in billion metric tonnes of carbon) Y gross domestic product, in billion US dollar. Source: FUND

	α	β	E	Y
USA	0.01515466	2.19648488	1.647	10399
CAN	0.01516751	0.09315600	0.124	807
WEU	0.01568000	3.15719404	0.762	12575
JPK	0.01562780	-1.42089104	0.525	8528
ANZ	0.01510650	-0.05143806	0.079	446
EEU	0.01465218	0.10131831	0.177	407
FSU	0.01381774	1.27242378	0.811	629
MDE	0.01434659	0.04737632	0.424	614
CAM	0.01486421	0.06652486	0.115	388
LAM	0.01513700	0.26839935	0.223	1351
SAS	0.01436564	0.35566631	0.559	831
SEA	0.01484894	0.73159104	0.334	1094
CHI	0.01444354	4.35686225	1.431	2376
NAF	0.01459959	0.96627119	0.101	213
SSA	0.01459184	1.07375825	0.145	302
SIS	0.01434621	0.05549814	0.038	55

3.2.1 The Welfare function of the FUND model

We approximate the FUND model with a linear benefit/quadratic cost structure for the analysis of coalition formation. Specifically, the abatement cost function is represented as:

$$C_i = \alpha_i R_i^2 Y_i \tag{3.1}$$

where C denotes abatement cost, R relative emission reduction, Y gross domestic product, indexes i denotes regions and α is the cost parameter. The benefit function is approximated as:

$$B_i = \beta_i \sum_j^n R_j E_j \tag{3.2}$$

where B denotes benefit, β the marginal damage costs of carbon dioxide emissions and E unabated emissions. Table (5.1) gives the parameters of Equations (5.1) and (5.2) as estimated by FUND. Moreover, the profit π_i of a country i is given as:

$$\pi_i = B_i - C_i = \beta_i \sum_j^n R_j E_j - \alpha_i R_i^2 Y_i \tag{3.3}$$

The second derivative of $d^2\pi_i/dR_i^2 = -2\alpha_i < 0$ as $\alpha_i > 0$. It follows that the profit function of every country i is strictly concave, and as a consequence has a unique maximum. Hence, the non-cooperative optimal emission reduction is found from first order optimal condition:

$$d\pi_i/dR_i = \beta_i E_i - 2\alpha_i R_i Y_i = 0 \Rightarrow R_i = \beta_i E_i/(2\alpha_i Y_i) \tag{3.4}$$

If a region i is in a coalition with region j, the optimal emission reduction is given by:

$$d\pi_{i+j}/dR_i = 0 \Rightarrow E_i(\beta_i + \beta_j) - 2\alpha_i R_i Y_i = 0 \Rightarrow R_i = (\beta_i + \beta_j)E_i/(2\alpha_i Y_i) \tag{3.5}$$

Thus, the price for entering a coalition is higher emission abatement at home. The return is that the coalition partners also raise their abatement efforts.
Note that our welfare functions are orthogonal. This indicates that the emissions change of a country do not affect the marginal benefits of other countries (that is the independence assumption). In our game, countries outside the coalition benefit from the reduction in emissions achieved by the cooperating countries, but they cannot affect the benefits derived by the members of the coalition. As our cost-benefit functions are orthogonal our approach does not capture the effects of emissions leakage. Even so our cost benefit functions are sufficiently realistic as they are an approximation of the complex model FUND and our procedure of dealing with farsighted stability is also general and appropriate for non-orthogonal functions.

3.3 Our model

There are 16 world regions (we name the set of all regions by N_{16}) in our game theoretic model of IEAs (or coalitions), which are shown in the first column of Table 5.1. At the first level, the link between the economic activity and the physical environment is established in order to generate the integrated assessment model. This link is established through a social welfare function calibrated to the FUND model (see equation 5.7). The social welfare function captures the difference between the profit from pollution and the environmental damage. Following this approach, countries play a two stage-game. In the first stage, each country decides whether to join the coalition $C \subseteq N_{16}$ and become a signatory (or coalition member) or stay singleton and non-signatory (*membership game*). These decisions lead to *coalition structure S* with *c* coalition-members and *16-c* non-members. *A coalition structure* fully describes how many coalitions are formed (presently we assume that we have one), how many members each coalition has and how many singleton players there are. In the second stage, every country decides on emissions (*strategic game*). Within the coalition, players play cooperatively (by maximizing their joint welfare) while the coalition and single countries compete in a non cooperative way (by maximizing their own welfare). Every coalition C is assigned a real number $v(C)$ (called the characteristic function).

Definition 3.1 *The **characteristic function** of our 16-player game (played by c and* $16 - c$ *players, where c is cardinality of coalition C) is a real-valued function:*
$\upsilon(C) : C \rightarrow \Re$,
$\upsilon(C) = max(\sum_1^c \pi_i) \quad \forall i \in C, \quad C \subset N_{16}, \quad c \leq 16.$

The characteristic function is simply the total profit that coalition members reach by maximizing their joint welfare. As the π_i are strictly concave, their sum is also strictly concave, which simplifies the maximization problem. The game satisfies the superadditivity property:

Definition 3.2 *A game is superadditive if for any two coalitions,* $C_1 \subset N_{16}$ *and* $C_2 \subset N_{16}$:
$\upsilon(C_1 \cup C_2) > \upsilon(C_1) + \upsilon(C_2) \quad C_1 \cap C_2 = \emptyset.$

The *superadditivity property* means that if C_1 and C_2 are disjoint coalitions (here C_1 and C_2 can be single players too), it is clear that they should accomplish at least as much by joining forces as by remaining separate. However the game *very frequently (but not always)* exhibits *positive spillovers:*

Definition 3.3 *A game exhibits positive spillover property if and only if for any two coalitions* $C_1 \subset N_{16}$ *and* $C_2 \subset N_{16}$ *such that* $C_1 \nsubseteq C_2$ *and* $C_2 \nsubseteq C_1$ *we have:*
$\forall k \notin C_1 \cup C_2 \quad \upsilon_k(C_1 \cup C_2) > \upsilon_k(C_1) \wedge \upsilon_k(C_1 \cup C_2) > \upsilon_k(C_2)$

It indicates that there is an external gain (C_1 and C_2 may be single players) or a positive spillover from cooperation, making free-riding (i.e., not joining $C_1 \cup C_2$) attractive. It implies that every player $k \notin C_1 \cup C_2$ has higher profit when two coalitions C_1 and C_2 cooperate in comparison to the situation where two coalitions remain separated. It indicates that from a non-signatory's point of view (player k here), the most favorable situation is the one in which all other countries take part in the coalition (except k). The positive spillover property is usually satisfied except for some coalitions that contain as members Japan & South Korea or Australia & New Zealand, which have negative marginal benefits (negative β's) from pollution abatement.
As our game is formally defined we return to our central question, namely farsighted stability. In our model framework, farsighted stability is mainly based on two arguments. The first one is the inducement process, which will be defined in the next subsection. The inducement raises the question: Can a subset of the members of our coalition improve their welfare (with the help of non-members or not) by forming a new coalition? The players are farsighted in the first sense that they check all possible ways (this is done by defining precisely the inducement process) for forming a new coalition in order to improve their welfare. The second argument is a behavioral assumption for the farsighted players that deters free riding. We assume that our players are farsighted in the sense that they refuse to free-ride because the other members of coalition can act similarly and this will ultimately result in a welfare decrease for all.

3.3.1 Farsighted stability and single farsightedly stable coalitions

In the first stage, the formation of *a single farsightedly stable coalition* is considered[3]. As we will consider only profitable coalitions, we define them from the beginning.

Definition 3.4 *The situation in which each country maximizes its own profit, and the maximum coalition size is unity is referred to as the atom structure.*

It is a standard Nash equilibrium. A coalition that performs better than the atom-structure is *a profitable coalition.* Only profitable coalitions are tested, which is sufficient to find all single farsightedly stable coalitions[4]. The definition of a profitable coalition is introduced below:

Definition 3.5 *A coalition C is profitable (or individual rational) if and only if it satisfies the following condition:*

$\forall i \in C \quad \pi(i)_C \geq \pi(i)_{ind}$

$\pi(i)_C$, $\pi(i)_{ind}$ *are the profits of country i as a member of C and in the atom structure respectively.*

Considering only profitable coalitions also reduces the computational effort required to find farsightedly stable coalitions.
Before presenting our approach of finding farsightedly stable coalitions, the definition of *inducement process* is presented below:

[3]We are going to provide a short introduction of how to define and find farsightedly stable coalitions. A detailed introduction is provided in Osmani & Tol (2009a).
[4]Some Observations in Osmani & Tol (2009a) provide the proof for this claim.

Definition 3.6 *A coalition C_n can be induced from any coalition C_1 if and only if:*

- *there exists a change sequence of coalitions $C_1, C_2 \dots C_{n-1}, C_n$ where $\pi_n(i) \geq \pi_1(i) \quad \forall i \in C_n$ and $C_1 \cap C_n \neq \emptyset$*

or

- *there exists a change sequence of coalitions $C_1, C_2 \dots C_{n-1}, C_n$ where $\pi_m(i) \geq \pi_1(i) \quad \forall i \in C_1 \wedge \forall i \notin C_n$ and $C_1 \subset C_2 \subset .. \subset C_{n-1} \subset C_n$*

$\pi_n(i)$, $\pi_m(i)$, $\pi_1(i)$ are profits, $\pi_1(i)$ refers to situations with C_1 and $\pi_n(i)$, $\pi_m(i)$ with C_n.

The first part of the inducement definition requires that all countries of the final coalition C_n do not decrease their profits and indirectly assumes that those countries have started the formation of the final coalition. The second part of the definition requires that all countries that leave the initial coalition C_1 (including free-riding) do not decrease their profits.
The definition of farsighted stability is based on the definition of the inducement process. This means, one needs to trace the inducement process in order to test whether a coalition is farsightedly stable or not. There are two main types of inducement process. In the first type, there is a change sequence of coalitions where *the countries in the final coalition* do not decrease their profits. In the second type, there is a change sequence of coalitions where *the countries that leave the initial coalition* do not decrease their profit. There are five classes of inducement process. Three of them belong to the first type of inducement process; the coalition grows bigger; gets smaller; some coalition-members leave coalition and some others join it. The last two classes of inducement process belong to the second type of inducement process. The fourth class is a special one, namely *free-riding*. One or more countries leaves the coalition and increase their welfare. The fifth inducement process is also a special inducement process which occurs only in *non-profitable coalitions* that have at least one country that has a welfare smaller than in the atom structure. Those countries are going to leave the coalition (and increase their welfare) *not due to free-riding* but because the joint welfare is distributed unfairly; there is no credible objection against those countries. Even if the coalition is dissolved and atom structure is reached, their welfare is higher than in the initial non-profitable coalition.
In order to find the farsightedly stable coalitions *all three inducement processes of **the first type** are considered as combinatorial process.* The fourth inducement, free-riding is deterred based on a behavioral assumption. The fifth inducement process occurs only in non-profitable coalitions, and as we discuss only profitable coalitions, we do not need to consider it for finding farsightedly stable coalitions[5].
We begin by conceiving the three inducement processes of the first type as a combinatorial process. If a coalition gets bigger, it follows that the original members see an increase in profit (or at least no decrease) and the new members see an increase too. We say that *an external inducement* is possible. This can be easily checked by a combinatorial algorithm.

Definition 3.7 *If no external inducement is possible then the coalition is externally farsightedly stable (EFS).*

If a coalition gets smaller, and its remaining members see an increase in profit, we say that *an internal inducement* is possible. This can be easily checked by a combinatorial algorithm too.

Definition 3.8 *If no internal inducement is possible then the coalition is internally farsightedly stable (IFS).*

The third class of coalition inducement occurs when a number of old coalition members leave and a number of new members join the coalition. The new coalition may be larger or smaller than the original one. One needs to check if a part of old coalition members (a sub-coalition), and the new coalition members can increase their profits by forming a coalition together. We call this *a sub-coalition inducement.* This case requires more combinatorial work to check if a sub-coalition inducement is possible.

Definition 3.9 *If no sub-coalition inducement is possible then the coalition is sub-coalition farsightedly stable (SFS).*

[5]However, the fifth inducement process is necessary in order to prove a couple of Observations in Osmani & Tol (2009a), which help to define (similar to Chwe 1994) the *Dynamic Large Consistent Set.* Note than any inducement process can be expressed as a combination of the five kinds of inducements which are mentioned above (when only one coalition is formed).

The definition of farsighted stability can be formulated:

Definition 3.10 *If no internal, external and sub-coalition inducement is possible then the coalition is farsightedly stable.*

Testing a coalition for farsighted stability means comparing the profit of country members with *the profit of country members of all possible coalitions (that can be induced or not) and finding the coalitions that can be induced.* We mention again as a crucial element of our approach, that coalitions, which contain our initial coalition as a subset, are inspected when the external farsighted stability is tested; the coalitions, that our initial coalition contains as subsets, are inspected when the internal farsighted stability is tested; and the coalitions, which have mutual members with our coalition, are inspected when the sub-coalition farsighted stability is tested.
We limit our attention to coalitions which are profitable. Thus at the beginning all profitable coalitions and then all single-farsightedly stable coalitions are found. The single farsightedly stable coalitions are (the superscript "fs" means farsightedly stable):

$(USA, CHI, NAF)^{fs}$ $(USA, CHI, SSA)^{fs}$ $(CAN, EEU, SAS)^{fs}$
$(CAN, FSU, LAM)^{fs}$ $(CAN, CAM, SAS)^{fs}$ $(CAN, SAS, SIS)^{fs}$
$(EEU, CAM, SAS)^{fs}$ $(EEU, SAS, SIS)^{fs}$ $(CAM, SAS, SIS)^{fs}$
$(CHI, NAF, SSA)^{fs}$

$(USA, LAM, CHI, NAF)^{fs}$ $(USA, LAM, CHI, SSA)^{fs}$ $(USA, SEA, CHI, NAF)^{fs}$
$(USA, SEA, CHI, SSA)^{fs}$ $(USA, CHI, NAF, SSA)^{fs}$ $(CAN, EEU, CAM, SAS)^{fs}$
$(CAN, EEU, SAS, SIS)^{fs}$ $(CAN, CAM, SAS, SIS)^{fs}$ $(EEU, CAM, SAS, SIS)^{fs}$
$(SEA, CHI, NAF, SSA)^{fs}$

$(USA, LAM, SEA, CHI, NAF)^{fs}$ $(USA, LAM, SEA, CHI, SSA)^{fs}$ $(USA, LAM, SEA, NAF, SSA)^{fs}$
$(USA, LAM, CHI, NAF, SSA)^{fs}$ $(USA, SEA, CHI, NAF, SSA)^{fs}$ $(CAN, EEU, CAM, SAS, SIS)^{fs}$
$(LAM, SEA, CHI, NAF, SSA)^{fs}$

$(USA, LAM, SEA, CHI, NAF, SSA)^{fs}$

In total, there are 56 profitable coalitions. By checking for external and sub-coalition stability, we find that we have 28 farsightedly stable coalitions: 1 six-member coalition, 7 five-member coalitions, 10 four-member coalitions and 10 three-member coalitions.
We find that all farsightedly stable coalitions are profitable. This is a consequence of the positive spillover property (that is very frequently satisfied) which implies that the cooperation (when a profitable coalition is formed) does not decrease the profit of countries that are not members of coalition. Therefore, farsighted stability is not a function of free-riding (like D'Aspremont myopic stability) *but farsighted stability is a function of profitability* which is difficult to satisfy for a single large coalition. Take coalition (6-1) $(USA, LAM, SEA, CHI, NAF, SSA)$. It is numerically checked that there is no larger profitable coalition that contains coalition (6-1) as subset. This implies that in all coalitions which contains coalition (6-1) as subset, there is at least one country that has a welfare smaller than in the atom structure. Those countries leave the coalition not due to free-riding but because the joint welfare is distributed unfairly (the fifth inducement process of second type occurs). There is no way (even farsighted way) to improve the welfare of these countries except by leaving the coalition or *by implementing a welfare transfer scheme.* Implementing a welfare transfer-scheme is not within the scope of this research which aims to find what coalition are stable in "selfish but farsighted world". As a consequence, it is natural that profitability condition is a border of "selfish but farsighted world", beyond this world the "farsighted and welfare-transferred world" begins which can possibly enable the existence of bigger stable coalitions.
It is essential to note that the *asymmetry of countries* does not allow *large profitable coalitions.* When coalition members maximize their joint welfare the optimization process requires further emissions reductions in those countries where it is cheaper to decrease emissions (where marginal abatement cost is low) until profit maximization is reached and the marginal abatement costs of coalition members are equal. As a result, those countries which initially have a low marginal abatement cost (if difference in marginal abatement cost among coalition members is also large before coalition formation) *will probably not satisfy the profitability condition.* On the other hand, the benefits from pollution abatement vary for different countries. This implies that countries that benefit less from pollution abatement, *will probably*

not satisfy the profitability condition. It follows that farsighted stability is a function of the asymmetry of countries. Free-riding does not allow large myopic stable coalitions and asymmetry of countries does not allow large farsightedly stable coalitions.

3.4 Single D'Aspremont stable coalitions

D'Aspremont stability considers only single-player movements. Therefore, players are myopic as they see only one movement ahead. A country that leaves the coalition assumes that the rest of coalition members stays in the coalition as well as non-members of the coalition (the country that does not belong to the coalition) remain non-members.

Definition 3.11 *A coalition S is internal D'Aspremont stable if and only if it satisfies the following condition:*

$\forall i \in S \quad \pi(i)_S > \pi(i)S - \{i\}$

$\pi(i)_S$ *is profit of a country i as a member S*
$\pi(i)S - \{i\}$ *are profit of a country i when he leaves the coalition S and the coalition $S - \{i\}$ is formed.*

A coalition is internal D'Aspremont stable if a country leaves the coalition, it decreases his profit.

Definition 3.12 *A coalition S is external D'Aspremont stable if and only if it satisfies the following condition:*

$\pi(j)_{S+\{j\}} < \pi(j)_{j \notin S}$ *or* $\exists\, i \in S| \quad \pi(i)_{S+\{j\}} < \pi(i)_S$

$\pi(j)_{S+\{j\}}$, $\pi(i)_{S+\{j\}}$ *are profits of countries j and i as a member of the coalition $S + \{j\}$*
$\pi(j)_{j \notin S}$ *is profit of a country j when the coalition S is formed but a country j is not a member of it*
$\pi(i)_S$ *is profit of a country i as a member the coalition S.*

A coalition is external D'Aspremont stable if a country joins the coalition, it decreases his profit or a previous member of coalition decreases its profit[6].
The definition of D'Apremont stability is stated below:

Definition 3.13 *A coalition S is D'Aspremont stable (or self-enforcing) if and only if it is profitable as well as internal and external D'Aspremont stable.*

In the beginning all profitable coalitions are found. Finding all profitable coalitions needs simple algorithm, although computational efforts are relatively not small. One finds all coalitions and checks if all their members have higher profit in comparison to atom structure. Then each coalition is checked if it is internal and external D'Aspremont stable.
All together there are ten D'Aspremont stable coalitions which are presented below:

(CAN, SAS), (ANZ, EEU), (ANZ, CAM),
(ANZ, SAS), (ANZ, SIS), (FSU, LAM),
(USA, CHI, NAF), (JPK, NAF, SSA), (CHI, NAF, SSA),
$(CAN, JPK, LAM, SAS, SSA)$,
$(CAN, JPK, EEU, CAM, LAM, NAF, SIS)$.

3.5 Preferred and dominated stable coalitions

The stability concept can be improved by looking carefully at the inducement process[7]. The inducement process means how much coalition-members can "see and change" in order to find the best coalition. Suppose we have a coalition structure (such as the atom structure) as a starting state that *cannot be induced* by two different farsightedly stable coalitions. The following question can be raised: *Which*

[6]In open membership games, the definition of D'Aspremont stability requests only that a country that joins coalition reduces his profit (Barrett 1994, Carraro et. al 2006). It is more realistic (as a exclusive membership game) to add the second part namely: or, a previous member of coalition reduces his profit.

[7]The discussion in this section is more relevant for farsighted stability, but it can somehow be applied to D'Aspremont stability too. We simply grant members of D'Aspremont stable coalitions the possibility of choosing among different myopic stable coalitions (which is an "ad-hoc" assumption).

farsightedly stable coalition is most likely to be formed from this starting point ? It is clear that the most usual starting point is the atom structure. We will compare the farsightedly stable coalitions not only with coalitions that originate from the general inducement process but also with the coalitions that originate from the most usual starting point, the atom structure. We can use this criterion in order to refine further our farsightedly stable coalitions.
The formal definition of *dominated coalition* is introduced below.

Definition 3.14 *A farsightedly stable coalition C_m is dominated if and only if:*

$$\forall \text{ country } i \in C_m \quad \exists\, C_{k_i} \quad |\pi_{C_{k_i}}(i) > \pi_{C_m}(i) \text{ and } C_{k_i} \text{ is a not-dominated farsighted stable coalition}$$

$$\pi_{C_{k_i}}(i),\ \pi_{C_m}(i) \text{ are profits of the country } i \text{ as a member } C_k \text{ and } C_m.$$

A coalition dominates another one if the country-members of first coalition get higher profit in comparison to the second one. It simply means that a country prefers the coalition where it gets higher profit.

Definition 3.15 *A coalition C_m is preferred over C_n, $C_m \succeq C_n$ if and only if:*

$$for\ the\ majority\ of\ country\ i \in C_m \cap C_n\ \pi_{C_m}(i) > \pi_{C_n}(i) \text{ and no coalition is preferred over } C_m$$

$$\pi_{C_m}(i),\ \pi_{C_n}(i) \text{ are profits of the country } i \text{ as a member } C_m \text{ and } C_n.$$

A coalition C_m is preferred over C_n if the majority of their mutual countries gets higher profit in C_m.
It is essential to note that if C_m is preferred to (or dominates) C_n then C_m cannot induce C_n or vice-versa (one can say *the inducement process* does not cover the *preference (dominance) relation*). Moreover, we see the dominance relation as a complement of the inducement process that somehow makes the inducement process complete. The coalitions that are more easily formed will be not only farsightedly stable but also preferred coalitions. Therefore, *the preferred (dominated) farsightedly stable coalitions* are more probably formed.

3.5.1 Preferred stable coalitions

One needs to perform numerical comparisons between coalitions that have mutual members in order to find preferred stable coalitions. We found out that preferred farsightedly stable coalitions are:

$(USA, LAM, SEA, CHI, NAF, SSA)$

$(CAN, EEU, CAM, SAS, SIS)$

The preferred D'Aspremont stable coalitions are:

(USA, CHI, NAF) (ANZ, SAS) and (FSU, LAM)

3.6 Multiple stable coalitions

In this section, the discussion is extended to the question of multiple stable coalitions. Note that the costs of emission reduction of a region are independent of the abatement of other regions and the benefits are linear. As a consequence in case of multiple coalitions the changes in the pay-off of each region is independent of the behavior of other regions provided that*the two coalitions do not exchange members.* It follows that our coalitions are stable if there is no inducement process which results in switching members between two coalitions. Besides we have numerically checked that there is no stable coalition that results from exchanging members between two stable coalitions. There are only two preferred farsightedly stable coalitions that exists simultaneously:

$(USA, LAM, SEA, CHI, NAF, SSA)^{fs}$

$(CAN, EEU, CAM, SAS, SIS)^{fs}$

The preferred D'Aspremont stable coalitions are:

(USA, CHI, NAF), (ANZ, SAS) and (FSU, LAM)

There are more multiple D'Aspremont stable coalitions than farsighted stable ones, but D'Aspremont stable coalitions have less coalition-members.

3.7 Comparing D'Aspremont and farsighted stability

The D'Aspremont stable coalition can be divided in three groups. The coalitions of first group are sub-coalitions of farsightedly stable coalition $(USA, LAM, SEA, CHI, NAF, SSA)$, and they are:

(USA, CHI, NAF), (CHI, NAF, SSA)

The coalitions of second group have members like ANZ and JPK which rarely form profitable coalition, and they are:

$(CAN, JPK, LAM, SAS, SSA)$

$(CAN, JPK, EEU, CAM, LAM, NAF, SIS)$

(ANZ, EEU), (ANZ, CAM)

(JPK, NAF, SSA)

The D'Aspremont coalitions of third group are small[8]:

(CAN, SAS), (ANZ, SAS), (ANZ, SIS), (FSU, LAM).

3.7.1 Conceptual discussion

We claim that the D'Aspremont stability is based on two myopic features. One is clear as it allows only single movement of a coalition member. The next feature is that it requests that there is no free-riding. If free riding exists it means that the profits form cooperation are big also. If there is no free-riding means that the profits from cooperation are small. We take the coalition (USA, CHI, NAF) (or (CHI, NAF, SSA)) of the first group of the D'Aspremont stable coalitions. There is no free-riding initiative as the coalition is internal D'Aspremont stable. This signifies that if a country leaves coalition it decreases its profit. However, this implies that any sub-coalition of two countries of our coalition does not reduce the emissions so much (the cooperation level is small) that a coalition member can take advantage of it and free-rides. Therefore, D'Aspremont coalition formation stops when free-riding appears. On the opposite the farsightedly stable coalition formation does not stop when free-riding appears, but it stops when the profitability condition is not satisfied any further. Consequently, one can build the following scheme for describing a way from D'Aspremont coalition to farsightedly stable coalition:

$$(USA, CHI) \Rightarrow \underbrace{(USA, CHI, NAF)^{ds}}_{myopic\ stable\ coalition} \Rightarrow \underbrace{(USA, CHI, NAF, SSA)}_{free-riding\ appears} \Rightarrow ... \Rightarrow \underbrace{(USA, LAM, SEA, CHI, NAF, SSA)^{fs}}_{profitability\ condition\ can\ not\ be\ satisfied\ further}$$

But this is better seen at Fig (3.1). In the y-axis we have single country profit in billion dollars. In the x-axis there are some possible coalitions from atom structure to D'Aspremont stable coalition (USA, CHI, NAF), and ends with farsightedly stable coalition $(USA, CHI, NAF, SSA, SEA, LAM)$. When:

$x = 1$ we have $Atom_{structure}$
$x = 2$ we have (USA, CHI)
$x = 3$ we have (USA, CHI, NAF)
$x = 4$ we have (USA, CHI, NAF, SSA)
$x = 5$ we have $(USA, CHI, NAF, SSA, SEA)$
$x = 6$ we have $(USA, CHI, NAF, SSA, SEA, LAM)$

Every line represents the profit change of the respective country when different coalitions are formed.

[8]We give a detailed explanation in the next subsection why we divide the D'Aspremont coalitions in these three groups.

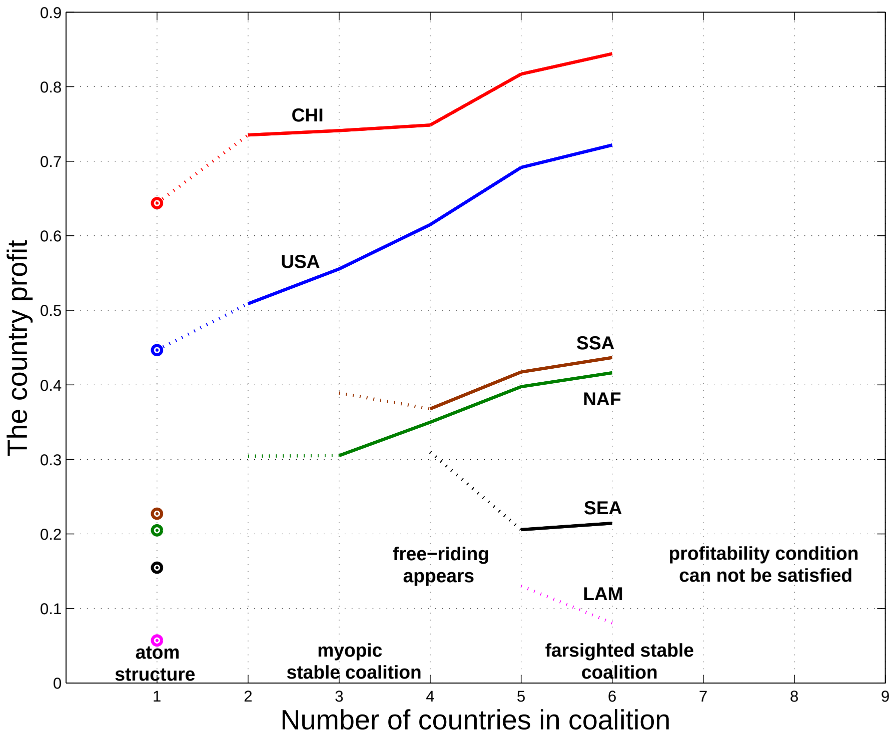

Figure 3.1: The comparison between the D'Aspremont and farsighted stability

In the beginning of the dotted line, the respective country is not a member of coalition. In the end of dotted line, the respective country joins the coalition. Countries that join the coalition, increase their profit, until the D'Aspremont stable coalition (USA, CHI, NAF) is formed. When the coalition (USA, CHI, NAF) is formed, every country that joins, decreases its profit. This indicates that the free-riding initiative exists as these coalitions are not internal D'Aspremont stable. After the farsightedly stable coalition $(USA, CHI, NAF, SSA, SEA, LAM)$ is formed, the profitability condition is not satisfied any longer. This suggests there is no bigger farsightedly stable coalition as *farsighted stability is a function of profitability* which is difficult to satisfy for a single large coalition. We have already clarified that the *asymmetry of countries* does not allow to have *large profitable coalitions*. This is a typical situation in D'Aspremont coalition formation, and implies that D'Aspremont stable coalitions frequently are subsets of farsightedly stable coalitions. As single farsightedly stable coalitions are not very large (only around 40 % of countries), this signifies that D'Aspremont stable coalitions are small (only around 20 % of countries). This occurs because *the internal D'Aspremont stability request no free-riding and no free-riding indicates that the cooperation brings only little improvements in welfare and environmental equality too* (this includes that the D'Aspremont stable coalitions are going to be small).
All coalitions of second group cause a decrease in abatement level and a worsening of environmental equality in comparison to atom structure. That is why they are grouped together. This takes place because they have as coalition member JPK or ANZ which can frequently (but not always) causes an abatement level decrease as they have negative marginal damage costs of carbon dioxide emissions β (or a negative marginal benefit from emissions reduction), see Table (5.1). We focus on the coalition $(CAN, JPK, EEU, CAM, LAM, NAF, SIS)$ (the discussion is similar for the other coalition of this group $(CAN, JPK, LAM, SAS, SSA)$) which belongs to the second group. Another distinctive feature of this coalition is that the cooperation is very "fragile", which means that if a country leaves the coalition than the coalition is not more profitable. This denotes that if a country leaves the coalition than the coalition does not exist any more and this stops the free-riding and even more. Besides the above coalition increases the welfare very little. Then we claim that internal D'Aspremont stability causes that we have big D'Aspremont coalitions (like $(CAN, JPK, EEU, CAM, LAM, NAF, SIS)$ or $(CAN, JPK, LAM, SAS, SSA)$) that have very "fragile" cooperation and bring a little improvement in

welfare, or we have D'Aspremont coalitions that are small (like (USA, CHI, NAF) and are sub-coalition of farsightedly stable coalitions). Concerning D'Aspremont coalitions, we reinforce the conclusions of Barrett (1994) which uses only stylized cost-benefit functions. As a conclusion, one can see *the D'Aspremont stable coalitions as "minimum" (in welfare, environment improvement, and frequently in coalition size), while the farsightedly stable coalition as "maximum"* that can be achieved by *game theory without side payments.* In real world coalition formation (like Kyoto protocol), it is more reasonable to expect that a part of players (countries) is myopic and a part of players is farsighted. Consequently, we should predict the formation of coalitions that are bigger than D'Aspremont stable but smaller than farsightedly stable coalitions.
The coalitions of third group have in common that they are small, and they improve the welfare and environmental equality (in spite of that two of them have ANZ as a member which has a negative marginal damage cost of carbon dioxide emissions β, see Table (5.1)).

3.7.2 Numerical computation

The D'Aspremont stable coalition that realizes the biggest improvements in welfare and abatement levels is (USA, CHI, NAF). This is a sub-coalition of the farsightedly stable coalition $(USA, CHI, NAF, SSA, SEA, LAM)$. The D'Apremont coalition (USA, CHI, NAF) increases the total welfare and abatement level in comparison to atom structure[9]. Besides the six member farsightedly stable coalition $(USA, LAM, SEA, CHI, NAF, SSA)$ raises the entire welfare and abatement level in comparison to D'Aspremont stable coalition[10] (USA, CHI, NAF).
The three preferred D'Apremont stable coalitions (USA, CHI, NAF), (ANZ, SAS) and (FSU, LAM) advance the welfare and abatement level in comparison to atom structure. Nevertheless, only the six member farsightedly stable coalition $(USA, LAM, SEA, CHI, NAF, SSA)$ raises the welfare and abatement in comparison to all *three preferred D'Apremont stable coalitions* together[11].
However, still the grand coalition performs far better than two farsightedly stable coalitions together $(USA, LAM, SEA, CHI, NAF, SSA)$ and $(CAN, EEU, CAM, SAS, SIS)$. The grand coalition improves the total profit more than 2 times and the abatement levels by almost 4 times in comparison to our two coalitions, and hence there is still a big space for improvement that due to selfishness of our players (countries) cannot be exploited[12].

3.8 Conclusion

The paper investigates the differences between the farsighted stability and D'Aspremont stability. The FUND model provides the cost-benefit functions of pollution abatement. The dynamic of damage-cost functions of the FUND model controls the results.
The D'Aspremont stability concept assumes that the players are myopic and considers only single-player movements. The farsighted stability captures the farsightedness of players. This implies that if a country considers deviating, it realizes that a deviation may trigger further deviations, which can worsen his initial position. All farsightedly stable and D'Aspremont stable coalitions are found as well as their improvements to welfare and environmental equality. There are a lot more farsighted stable coalitions than D'Apremont stable coalitions, so the farsighted stability enlarges the space of cooperation.
We refine further the stable coalitions (farsighted stable or D'Aspremont stable) to preferred stable coalition. The preferred stable coalitions are more probable to form from a usual starting state such as atom structure in comparison to other stable coalitions.
We argue that D'Aspremont stability is myopic in two senses. Firstly, because it considers only single-player movements. Secondly, because the internal D'Aspremont stability requests no free-riding. Nevertheless, no free-riding means that improvements (in welfare and environmental equality) from cooperation are small. Therefore, the internal D'Aspremont stability indirectly requests that the improvements from cooperation are small.

[9] The D'Apremont coalition (USA, CHI, NAF) increases the welfare by 47 % and abatement level by 91 % in comparison to atom structure.

[10] However, the six member farsightedly stable coalition $(USA, LAM, SEA, CHI, NAF, SSA)$ raises the whole welfare and abatement respectively by 27 % and 97 % in comparison to D'Aspremont stable coalition (USA, CHI, NAF).

[11] The three preferred D'Apremont stable coalitions (USA, CHI, NAF), (ANZ, SAS) and (FSU, LAM) improve the welfare by 53 % and abatement level by a factor 2 in comparison to atom structure. The six member farsightedly stable coalition $(USA, LAM, SEA, CHI, NAF, SSA)$ improves the welfare and abatement respectively by 20 % and 79 % in comparison to all *three preferred D'Apremont stable coalitions* together.

[12] A part of the numerical computation is already introduced shortly in Osmani & Tol (2009).

The size of largest single farsightedly stable coalition and D'Aspremont stable coalition is small. The D'Aspremont stability argues that the free-riding makes difficult to have large single stable coalitions. On the opposite the farsighted stability argues that due to the asymmetry, the profitability condition is hard to be satisfied for large single farsightedly stable coalitions. Moreover, the asymmetry of countries makes profitability condition hard to be realized and avoids maintaining big farsightedly stable coalitions. In spite of single D'Aspremont coalitions are very small (only three countries) they bring improvement in comparison to atom structure. However, the farsightedly stable coalitions improve the welfare and environmental equality in comparison to D'Aspremont stable coalitions.

We show that the D'Aspremont stable coalitions are often sub-coalitions of farsightedly stable coalitions. Moreover, farsightedly stable coalitions can be frequently the biggest size stable coalitions that game theory without side payments can attain. Furthermore, they produce always the biggest improvement in environmental and welfare. In real world coalition formation (like Kyoto protocol), it is more reasonable to expect that a part of players (countries) is myopic and a part of players is farsighted. Consequently, we should predict the formation of coalitions that are bigger than D'Aspremont stable but smaller than farsightedly stable coalitions.

Considering the multiple farsightedly stable coalitions leads to an optimistic result of game theory. Almost 70 % of regions (around 40 % of countries cooperate in case of multiple D'Apremont stable coalitions) can cooperate and improve significantly the welfare and environmental quality. The multiple D'Aspremont stable coalitions significantly improve the welfare in comparison to atom structure. However, the multiple farsightedly stable coalitions clearly increase the welfare and abatement levels compare to multiple D'Aspremont stable coalitions.

It will be interesting to consider more detailed regions and a game theoretic approach with side payments.

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Chapter 4

Evolution in Time of Farsightedly Stable Coalitions

Evolution in time of Farsightedly Stable Coalitions

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Abstract

Game theory is used to analyze the formation and stability of coalitions for environmental protection. The paper extends further our previous research on farsightedly stable coalitions and preferred farsightedly stable coalitions (Osmani & Tol 2009a). The integrated assessment model FUND provides data for different time horizons as well as the cost-benefit function of pollution abatement. This allows for analysis of the evolution in time of farsightedly stable coalitions and their improvement to environment and welfare. Considering multiple farsightedly stable coalitions, the participation in coalitions for environmental protection is significantly increased, which is a positive result of the game theoretical approach. However, the farsighted behavior can not be sustained for a long term which implies there are no big coalitions for environmental protection even in "a farsighted world".

Keywords: game theory, integrated assessment modeling, farsighted stability, coalition formation.

JEL: C02, C72, H41

4.1 Introduction

A considerable part of the literature uses game theory as a tool to realize the formation mechanism of International Environmental Agreements (IEA). There are two major views of literature on IEAs (for a review of current literature see Finus 2003; Carraro/Siniscalco 1998; Ioannidis/Papandreou/Sartzetakis 2000; Carraro/Eyckmans/Finus 2005). The first direction (Chander & Tulkens 1997, Chander & Tulkens 2006, Eyckmans & Tulkens 2003, Chander 2007) shows that the grand coalition is stable, assuming transferable utility, then using the γ-core concept and implementing transfers to solve the heterogeneity of the countries involved. This is a rather optimistic view. The second direction uses the concepts of non-cooperative game theory to model the formation of IEAs (Barrett 1994, Barrett 2003, Botteon & Carraro 2001, Osmani & Tol 2005, Finus & Ierland & Dellnik 2006, Rubio & Ulph 2006, McGinty 2007). The usual approach of non-cooperative game theory to stable IEAs is based on the idea developed for cartel stability (d'Aspremont et al. (1983)) and requires so-called internal and external stability. Internal stability means that a country does not have an incentive to leave the coalition, while external stability means that a country does not have an incentive to join the coalition. This part of the literature reaches the conclusion that the size of a stable coalition is typically very small, thus representing a pessimistic view of global environmental goods.

At the first level, the link between the economic activity and the physical environment is established in order to generate the integrated-assessment model. This link is established through a social welfare function. The social welfare function captures the difference between the profit from pollution and the environmental damage.

The Climate Framework for Uncertainty, Negotiation and Distribution (FUND, see Section 4.2) model provide the social-welfare functions.

Following this approach, countries play a two stage-game. In the first stage, each country decides to join

the IEA or not, and in the second stage, a country decides on emissions. The main body of literature examining the formation of IEA within a two stage framework uses a certain set of assumptions. The essential assumptions are mentioned below: decisions are simultaneous in both stages, countries can form single coalition; stability of IEA's is based on the ideas developed for cartel stability (d'Aspremont et al. (1983)) and requires so-called internal and external stability; internal stability means that a country does not have an incentive to leave the coalition while external stability means that a country does not have an incentive to join the coalition; when defecting from coalition, a country assumes that all other countries remain in the coalition (this is a consequence of the employed stability concept of d'Aspremont *et al* that allows only singleton movements and myopia); within the coalition, players play cooperatively and maximize their joint welfare, while the coalition and single countries compete in a non cooperative way.
Non-cooperative game theory draws a pessimistic picture of the prospect of successful cooperation between countries. It claims that a large coalition of signatories is hardly stable, and that the free-rider incentive is strong. The model explains the problems of international cooperation in the attendance of environmental spillovers, but cannot explain IEAs with high membership such as the Montreal Protocol on Ozone Depleting Substances. This calls for a modification of the standard assumptions. Following, I mention some of the modifications.
Asheim et. al (2006), Carraro (2000) and Osmani & Tol (2005) allow more than one IEA to be formed. They reach the conclusion that two IEA's can perform better than one IEA in regional environmental problems but not in global ones.
Diamantoudi & Sartzetakis (2002), Eyckmans (2003) and Osmani & Tol (2009a, 2009b) use the farsighted stability concept instead of d'Aspremont myopic stability. The farsighted stability is firstly introduced by Chwe (1994). The idea of farsightedness means that one should check for multi-step stability by comparing the profits of a coalition member after a series of deviations has come to an end.
This research develops further our previous work (Osmani & Tol 2007a) on farsightedly stable coalitions and preferred farsightedly stable coalitions. In our previous paper, we show that multiple preferred farsightedly stable coalitions include two thirds of countries and improve significantly the welfare and environment which are optimistic results. Here the discussion is extended on the issue, which farsightedly stable coalitions are more likely to form in different time horizons and how much improvements they bring to welfare and environment. I raise the question if the farsightedly stable coalitions can be maintained for a long-term period. The improvements in welfare and abatement levels of full non-cooperative behavior (atom structure) and grand coalition are considered also.
The benefit-cost functions come form the *Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model* which is described in section two. The next section presents the game-theoretic model, and a discussion on single farsightedly stable coalitions. The preferred and dominated farsightedly stable coalition are considered in section four. In section four multiple preferred farsightedly stable coalitions are taken into account. The following section examines why are preferred farsightedly stable coalitions varying in different time horizons. Section eight provides the conclusions. I discuss in Appendix the winners and losers from participation in coalitions for environmental protection for different year horizons.

4.2 FUND model

This paper uses version 2.8 of the Climate Framework for Uncertainty, Negotiation and Distribution (FUND).
Essentially, FUND consists of a set of exogenous scenarios and endogenous perturbations. The model distinguishes 16 major regions of the world, viz. the United States of America (USA), Canada (CAN), Western Europe (WEU), Japan and South Korea (JPK), Australia and New Zealand (ANZ), Central and Eastern Europe (EEU), the former Soviet Union (FSU), the Middle East (MDE), Central America (CAM), South America (LAM), South Asia (SAS), Southeast Asia (SEA), China (CHI), North Africa (NAF), Sub-Saharan Africa (SSA), and Small Island States (SIS). The model runs from 1950 to 2300 in time steps of one year. The prime reason for starting in 1950 is to initialize the climate change impact module. The period of 1950-1990 is used for the calibration of the model, which is based on the IMAGE 100-year database (Batjes, Goldewijk, 1994). The period 1990-2000 is based on observations (WRI, 2000). The climate scenarios for the period 2010-2100 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett et al., 1992). The 2000-2010 period is interpolated from the immediate past, and the period 2100-2300 extrapolated.
The scenarios are defined by the rates of population growth, economic growth, autonomous energy ef-

ficiency improvements as well as the rate of decarbonization of the energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from land use change, methane and nitrous oxide. The scenarios of economic and population growth are perturbed by the impact of climatic change. Population decreases with increasing climate change related deaths that result from changes in heat stress, cold stress,malaria, and tropical cyclones.

The endogenous parts of FUND consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, the impact of carbon dioxide emission reductions on the economy and on emissions, and the impact of the damages to the economy and the population caused by climate change. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is represented by the five-box model of Maier-Reimer and Hasselmann (1987). Its parameters are taken from Hammitt et al. (1992). The model also contains sulphur emissions (Tol, 2006).

The climate impact module, based on Tol (2002b,c) includes the following categories: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems. Climate change related damages can be attributed to either the rate of change (benchmarked at 0.04°C) or the level of change (benchmarked at 1.0°C).

4.2.1 The Welfare function of the FUND model

The FUND model is approximated with a linear benefit/quadratic cost structure for the analysis of coalition formation. Specifically, the abatement cost function is represented as:

$$C_i = \alpha_i R_i^2 Y_i \tag{4.1}$$

where C denotes abatement cost, R relative emission reduction, Y gross domestic product, indexes i denotes regions and α is the cost parameter. The benefit function is approximated as:

$$B_i = \beta_i \sum_j^n R_j E_j \tag{4.2}$$

where B denotes benefit, β the marginal damage costs of carbon dioxide emissions and E unabated emissions. Table 4.1, 4.2, 4.3 and 4.4 give the parameters of Equations (5.1) and (5.2) as estimated by FUND. Moreover, the profit π_i of a country i is given as:

$$\pi_i = B_i - C_i = \beta_i \sum_j^n R_j E_j - \alpha_i R_i^2 Y_i \tag{4.3}$$

The second derivative of $d^2\pi_i/dR_i^2 = -2\alpha_i < 0$ as $\alpha_i > 0$. It follows that the profit function of every country i is strictly concave, and as a consequence has a unique maximum. Hence, the non-cooperative optimal emission reduction is found from first order optimal condition:

$$d\pi_i/dR_i = \beta_i E_i - 2\alpha_i R_i Y_i = 0 \Rightarrow R_i = \beta_i E_i/(2\alpha_i Y_i) \tag{4.4}$$

If a region i is in a coalition with region j, the optimal emission reduction is given by:

$$d\pi_{i+j}/dR_i = 0 \Rightarrow E_i(\beta_i + \beta_j) - 2\alpha_i R_i Y_i = 0 \Rightarrow R_i = (\beta_i + \beta_j)E_i/(2\alpha_i Y_i) \tag{4.5}$$

Thus, the price for entering a coalition is higher emission abatement at home. The return is that the coalition partners also raise their abatement efforts.

Note that the welfare functions are orthogonal. This indicates that the emissions change of a country do not affect the marginal benefits of other countries (that is the independence assumption). In the game-theoretic approach, countries outside the coalition benefit from the reduction in emissions achieved by the cooperating countries, but they cannot affect the benefits derived by the members of the coalition. As the cost-benefit functions are orthogonal, this approach does not capture the effects of emissions leakage. Even so the cost benefit functions are sufficiently realistic as they are an approximation of the complex model FUND and the procedure of dealing with farsighted stability is also general and appropriate for non-orthogonal functions.

4.3 The model

There are 16 world regions (the set of all regions is named by N_{16}) in the game theoretic model of IEAs (or coalitions), which are shown in the first column of Table 4.1 too. At the first level, the link between the economic activity and the physical environment is established in order to generate the integrated assessment model. This link is established through a social welfare function calibrated to the FUND model (see equation 5.7). The social welfare function captures the difference between the profit from pollution and the environmental damage. Following this approach, countries play a two stage-game. In the first stage, each country decides whether to join the coalition $C \subseteq N_{16}$ and become a signatory (or coalition member) or stay singleton and non-signatory (*membership game*). These decisions lead to *coalition structure S* with c coalition-members and *16-c* non-members. *A coalition structure* fully describes how many coalitions are formed (presently I assume that there is only one), how many members each coalition has and how many singleton players there are. In the second stage, every country decides on emissions (*strategic game*). Within the coalition, players play cooperatively (by maximizing their joint welfare) while the coalition and single countries compete in a non cooperative way (by maximizing their own welfare). Every coalition C is assigned a real number $\upsilon(C)$ (called the characteristic function).

Definition 4.1 *The* ***characteristic function*** *of 16-player game (played by c and* $16 - c$ *players, where c is cardinality of coalition C) is a real-valued function:*
$\upsilon(C) : C \to \Re$,
$\upsilon(C) = max(\sum_1^c \pi_i) \quad \forall i \in C, \quad C \subset N_{16}, \quad c \leq 16.$

The characteristic function is simply the total profit that coalition members reach by maximizing their joint welfare. As the π_i are strictly concave, their sum is also strictly concave, which simplifies the maximization problem. The game satisfies the superadditivity property:

Definition 4.2 *A game is superadditive if for any two coalitions,* $C_1 \subset N_{16}$ *and* $C_2 \subset N_{16}$:
$\upsilon(C_1 \cup C_2) > \upsilon(C_1) + \upsilon(C_2) \quad C_1 \cap C_2 = \emptyset.$

The *superadditivity property* means that if C_1 and C_2 are disjoint coalitions (here C_1 and C_2 can be single players too), it is clear that they should accomplish at least as much by joining forces as by remaining separate. However the game *very frequently (but not always)* exhibits *positive spillovers:*

Definition 4.3 *A game exhibits positive spillover property if and only if for any two coalitions* $C_1 \subset N_{16}$ *and* $C_2 \subset N_{16}$ *such that* $C_1 \nsubseteq C_2$ *and* $C_2 \nsubseteq C_1$ *we have:*
$\forall k \notin C_1 \cup C_2 \quad \upsilon_k(C_1 \cup C_2) > \upsilon_k(C_1) \wedge \upsilon_k(C_1 \cup C_2) > \upsilon_k(C_2)$

It indicates that there is an external gain (C_1 and C_2 may be single players) or a positive spillover from cooperation, making free-riding (i.e., not joining $C_1 \cup C_2$) attractive. It implies that every player $k \notin C_1 \cup C_2$ has higher profit when two coalitions C_1 and C_2 cooperate in comparison to the situation where two coalitions remain separated. It indicates that from a non-signatory's point of view (player k here), the most favorable situation is the one in which all other countries take part in the coalition (except k). The positive spillover property is usually satisfied except for some coalitions that contain as members Japan & South Korea or Australia & New Zealand, which have negative marginal benefits (negative β's) from pollution abatement.
As the game is formally defined I return to central question of the paper, namely farsighted stability. In this model framework, farsighted stability is mainly based on two arguments. The first one is the inducement process, which will be defined in the next subsection. The inducement raises the question: Can a subset of the members of a coalition improve their welfare (with the help of non-members or not) by forming a new coalition? The players are farsighted in the first sense that they check all possible ways (this is done by defining precisely the inducement process) for forming a new coalition in order to improve their welfare. The second argument is a behavioral assumption for the farsighted players that deters free riding. I assume that players are farsighted in the sense that they refuse to free-ride because the other members of coalition can act similarly and this will ultimately result in a welfare decrease for all.

4.3.1 Farsighted stability and single farsightedly stable coalitions

In the first stage, the formation of *a single farsightedly stable coalition* is considered[1]. As only profitable coalitions are considered, I define them from the beginning.

[1]A short introduction of how to define and find farsightedly stable coalitions is provided. A detailed introduction is provided in Osmani & Tol (2009a).

Definition 4.4 *The situation in which each country maximizes its own profit, and the maximum coalition size is unity is referred to as the atom structure.*

It is a standard Nash equilibrium. A coalition that performs better than the atom-structure is *a profitable coalition*. Only profitable coalitions are tested, which is sufficient to find all single farsightedly stable coalitions[2]. The definition of a profitable coalition is introduced below:

Definition 4.5 *A coalition C is profitable (or individual rational) if and only if it satisfies the following condition:*

$\forall i \in C \quad \pi(i)_C \geq \pi(i)_{ind}$

$\pi(i)_C$, $\pi(i)_{ind}$ *are the profits of country* i *as a member of* C *and in the atom structure respectively.*

Considering only profitable coalitions also reduces the computational effort required to find farsightedly stable coalitions.
Before presenting the approach of finding farsightedly stable coalitions, the definition of *inducement process* is presented below:

Definition 4.6 *A coalition* C_n *can be induced from any coalition* C_1 *if and only if:*

- *there exists a change sequence of coalitions* $C_1, C_2 \ldots C_{n-1}, C_n$
  where $\pi_n(i) \geq \pi_1(i) \quad \forall i \in C_n$ *and* $C_1 \cap C_n \neq \emptyset$

  or

- *there exists a change sequence of coalitions* $C_1, C_2 \ldots C_{n-1}, C_n$
  where $\pi_m(i) \geq \pi_1(i) \quad \forall i \in C_1 \wedge \forall i \notin C_n$ *and* $C_1 \subset C_2 \subset .. \subset C_{n-1} \subset C_n$

$\pi_n(i)$, $\pi_m(i)$, $\pi_1(i)$ *are profits,* $\pi_1(i)$ *refers to situations with* C_1 *and* $\pi_n(i)$, $\pi_m(i)$ *with* C_n.

The first part of the inducement definition requires that all countries of the final coalition C_n do not decrease their profits and indirectly assumes that those countries have started the formation of the final coalition. The second part of the definition requires that all countries that leave the initial coalition C_1 (including free-riding) do not decrease their profits.
The definition of farsighted stability is based on the definition of the inducement process. This means, one needs to trace the inducement process in order to test whether a coalition is farsightedly stable or not. There are two main types of inducement process. In the first type, there is a change sequence of coalitions where *the countries in the final coalition* do not decrease their profits. In the second type, there is a change sequence of coalitions where *the countries that leave the initial coalition* do not decrease their profit. There are five classes of inducement process. Three of them belong to the first type of inducement process; the coalition grows bigger; gets smaller; some coalition-members leave coalition and some others join it. The last two classes of inducement process belong to the second type of inducement process. The fourth class is a special one, namely *free-riding*. One or more countries leaves the coalition and increase their welfare. The fifth inducement process is also a special inducement process which occurs only in *non-profitable coalitions* that have at least one country that has a welfare smaller than in the atom structure. Those countries are going to leave the coalition (and increase their welfare) *not due to free-riding* but because the joint welfare is distributed unfairly; there is no credible objection against those countries. Even if the coalition is dissolved and atom structure is reached, their welfare is higher than in the initial non-profitable coalition.
In order to find the farsightedly stable coalitions *all three inducement processes of* ***the first type*** *are considered as combinatorial process.* The fourth inducement, free-riding is deterred based on a behavioral assumption. The fifth inducement process occurs only in non-profitable coalitions, and as only profitable coalitions are taken into account, I do not need to consider it for finding farsightedly stable coalitions[3].
I begin by conceiving the three inducement processes of the first type as a combinatorial process. If a coalition gets bigger, it follows that the original members see an increase in profit (or at least no decrease) and the new members see an increase too. I consider that *an external inducement* is possible. This can be easily checked by a combinatorial algorithm.

[2]Some Observations in Osmani & Tol (2009a) provide the proof for this claim.

[3]However, the fifth inducement process is necessary in order to prove a couple of Observations in Osmani & Tol (2009a), which help to define (similar to Chwe 1994) the *Dynamic Large Consistent Set.* Note than any inducement process can be expressed as a combination of the five kinds of inducements which are mentioned above (when only one coalition is formed).

Definition 4.7 *If no external inducement is possible then the coalition is externally farsightedly stable (EFS).*

If a coalition gets smaller, and its remaining members see an increase in profit, I consider say that *an internal inducement* is possible. This can be easily checked by a combinatorial algorithm too.

Definition 4.8 *If no internal inducement is possible then the coalition is internally farsightedly stable (IFS).*

The third class of coalition inducement occurs when a number of old coalition members leave and a number of new members join the coalition. The new coalition may be larger or smaller than the original one. One needs to check if a part of old coalition members (a sub-coalition), and the new coalition members can increase their profits by forming a coalition together. This is called *a sub-coalition inducement.* This case requires more combinatorial work to check if a sub-coalition inducement is possible.

Definition 4.9 *If no sub-coalition inducement is possible then the coalition is sub-coalition farsightedly stable (SFS).*

The definition of farsighted stability can be formulated:

Definition 4.10 *If no internal, external and sub-coalition inducement is possible then the coalition is farsightedly stable.*

Testing a coalition for farsighted stability means comparing the profit of country members with *the profit of country members of all possible coalitions (that can be induced or not) and finding the coalitions that can be induced.* I mention again as a crucial element of this approach, that coalitions, which contain the initial coalition as a subset, are inspected when the external farsighted stability is tested; the coalitions, that the initial coalition contains as subsets, are inspected when the internal farsighted stability is tested; and the coalitions, which have mutual members with the initial coalition, are inspected when the sub-coalition farsighted stability is tested.

One special inducement process is caused by free-riding. As already noted, free-riding is prevented based on reasoning that originates from experimental game theory (Fehr & Gaechter 2000, Ostrom 2000), which predicts that if a player free-rides[4], as the rest of players receive this information, some (not all) of them will also free-ride. This will result in worsening the welfare of every player. I suppose that players (countries) possess the knowledge that if free-riding appears, it will expand and other players will start to free-ride. This assumption deters free-riding and fits well with farsighted behavior, as it takes into account the counter reaction of other players. As free-riding is prevented based on this behavioral assumption, which implies that there is no free-riding for any coalition, then the inducement caused by free-riding cannot be included in definition of farsighted stability.

Therefore, farsighted stability is not a function of free-riding (like D'Aspremont myopic stability) *but farsighted stability is a function of profitability* which is difficult to satisfy for a single large coalition. Take coalition (6-1) ($USA, LAM, SEA, CHI, NAF, SSA$). It is numerically checked that there is no larger profitable coalition that contains coalition (6-1) as subset. This implies that in all coalitions which contains coalition (6-1) as subset, there is at least one country that has a welfare smaller than in the atom structure. Those countries leave the coalition not due to free-riding but because the joint welfare is distributed unfairly (the fifth inducement process of second type occurs). There is no way (even farsighted way) to improve the welfare of these countries except by leaving the coalition or *by implementing a welfare transfer scheme.* Implementing a welfare transfer-scheme is not within the scope of this research which aims to find what coalition are stable in "selfish but farsighted world". As a consequence, it is natural that profitability condition is a border of "selfish but farsighted world", beyond this world the "farsighted and welfare-transferred world" begins which can possibly enable the existence of bigger stable coalitions.

It is essential to note that the *asymmetry of countries* does not allow *large profitable coalitions.* When coalition members maximize their joint welfare the optimization process requires further emissions reductions in those countries where it is cheaper to decrease emissions (where marginal abatement cost is low) until profit maximization is reached and the marginal abatement costs of coalition members are equal. As a result, those countries which initially have a low marginal abatement cost (if difference in marginal abatement cost among coalition members is also large before coalition formation) *will probably*

[4]Unfortunately, the referenced papers consider behavior of people not of countries.

not satisfy the profitability condition. On the other hand, the benefits from pollution abatement vary for different countries. This implies that countries that benefit less from pollution abatement, *will probably not satisfy the profitability condition.* It follows that farsighted stability is a function of the asymmetry of countries. Free-riding does not allow large myopic stable coalitions and asymmetry of countries does not allow large farsightedly stable coalitions.

4.3.2 Farsightedly stable coalitions for different time horizons

Finding all profitable coalitions needs simple algorithm, although computational efforts are not small. One finds all coalitions and checks if all their members have higher profits in comparison to atom structure.
The computation of all farsightedly stable coalitions is time consuming and not always necessary. That is why I calculate all of them only for year 2005 and part of them for years 2025 and 2045. Only *the preferred farsightedly stable coalitions* are calculated for years 2015 and 2035. The preferred farsightedly stable coalitions are a refinement of farsightedly stable coalitions (see next section).
For year 2005, there are more than fifty profitable coalitions and 29 farsightedly stable coalitions[5].
For year 2025, there are more than three hundred profitable coalitions and at least 159 farsightedly stable coalitions[6].
For year 2045, there are again more than three hundred profitable coalitions and at least 101 farsightedly stable coalitions[7].
As it is already shown there are many farsightedly stable coalitions[8]. The set of all farsightedly stable coalitions is called *farsighted cooperation space.* The farsighted cooperation space is big, it implies that a lot of countries have economic incentives to participate in coalitions for environmental protection like Kyoto protocol.

4.4 Preferred and dominated farsightedly stable coalitions

The farsighted stability concept can be improved by looking carefully at the inducement process. The inducement process means how much coalition-members can "see and change" in order to find the best coalition. Suppose that a coalition structure (such as the atom structure) is a starting state that *cannot be induced* by two different farsightedly stable coalitions. The following question can be raised: *Which farsightedly stable coalition is most likely to be formed from this starting point ?* It is clear that the most usual starting point is the atom structure. I will compare the farsightedly stable coalitions not only with coalitions that originate from the general inducement process but also with the coalitions that originate from the most usual starting point, the atom structure. This criterion can be used in order to refine further the farsightedly stable coalitions.
The formal definition of *dominated coalition* is introduced below.

Definition 4.11 *A farsightedly stable coalition C_m is dominated if and only if:*

$\forall$ *country* $i \in C_m \quad \exists\, C_{k_i} \quad |\pi_{C_{k_i}}(i) > \pi_{C_m}(i)$ *and* C_{k_i} *is a not-dominated farsighted stable coalition*

$\pi_{C_{k_i}}(i),\ \pi_{C_m}(i)$ *are profits of the country i as a member C_k and C_m.*

[5]There are 56 profitable coalitions. By checking for internal, external and sub-coalition stability, there are 29 farsightedly stable coalitions: 1 seven-member coalition, 1 six-member coalition 7 five-member coalitions, 10 four-member coalitions and 10 three-member coalitions

[6]There are 374 profitable coalitions. The number of profitable coalitions is increased by a factor 6 in comparison to the year 2005. Numerical computation shows that there are 5 nine-members farsightedly stable coalitions, 27 eight-members farsightedly stable coalitions, 58 seven-members farsightedly stable coalitions and 69 six-members farsightedly stable coalitions. Therefore, there are at least 159 farsightedly stable coalitions as I have not considered the farsightedly stable coalitions with less than six members. So, there are at least 5 times more farsightedly stable coalitions in comparison to year 2005.

[7]There are 365 profitable coalitions. The number of profitable coalitions is less in comparison to the year 2025. Numerical computation shows that there are 1 nine-members farsightedly stable coalitions, 7 eight-members farsightedly stable coalitions, 47 seven-members farsightedly stable coalitions and 46 four-members farsightedly stable coalitions. Consequently, there are at least 101 farsightedly stable coalitions as I have not considered the five and six-members farsightedly stable coalitions as well as those with less than four-members. I think that there are less farsightedly stable coalitions in comparison to the year 2025 but there are three times more farsightedly stable coalitions in comparison to year 2005

[8]There are 80 profitable coalitions for year 2015, and 337 for year 2035. I expect that there are many farsightedly stable coalitions for these years too.

A coalition dominates another one if the country-members of first coalition get higher profit in comparison to the second one. It simply means that a country prefers the coalition where it gets higher profit.

Definition 4.12 *A coalition C_m is preferred over C_n, $C_m \succeq C_n$ if and only if:*

$$for\ the\ majority\ of\ country\ i \in C_m \cap C_n\ \pi_{C_m}(i) > \pi_{C_n}(i)\ \text{and no coalition is preferred over } C_m$$

$\pi_{C_m}(i)$, $\pi_{C_n}(i)$ *are profits of the country i as a member C_m and C_n.*

A coalition C_m is preferred over C_n if the majority of their mutual countries gets higher profit in C_m. It is essential to note that if C_m is preferred to (or dominates) C_n then C_m cannot induce C_n or vice-versa (one can say *the inducement process* does not cover the *preference (dominance) relation*). Moreover, I see the dominance relation as a complement of the inducement process that somehow makes the inducement process complete. The coalitions that are more easily formed will be not only farsightedly stable but also preferred coalitions. Therefore, *the preferred (dominated) farsightedly stable coalitions* are more probably formed.

4.5 Multiple preferred farsightedly stable coalitions

In this section, the discussion is extended to the question of multiple farsightedly stable coalitions. Note that the costs of emission reduction of a region are independent of the abatement of other regions and the benefits are linear. As a consequence in case of multiple coalitions the changes in the pay-off of each region is independent of the behavior of other regions provided that *coalitions do not exchange members.* It follows that coalitions are farsightedly stable if there is no inducement process which results in switching members between two coalitions. Besides I have numerically checked that there is no PFS coalition that results from exchanging members between two PFS coalitions which belong to the same year horizon.
Thus, for each of years 2005, 2015, 2025, 2035 and 2045, there are two PFS coalitions that exists simultaneously which are presented below (see Fig 4.1 also):

$(CAN, EEU, CAM, SAS, SIS)^{2005}$
$(USA, LAM, SEA, CHI, NAF, SSA)^{2005}$

$(CAN, EEU, FSU, CAM, LAM, SAS, SIS)^{2015}$
$(USA, WEU, CHI, NAF, SSA)^{2015}$

$(ANZ, EEU, FSU, MDE, CAM, LAM, SAS, SEA, SIS)^{2025}$
$(USA, WEU, CHI, NAF, SSA)^{2025}$

$(ANZ, EEU, FSU, MDE, CAM, LAM, SAS, SIS)^{2035}$
$(USA, NAF, SSA)^{2035}$

$(JPK, EEU, FSU, MDE, SAS, SIS)^{2045}$
$(USA, CAN, ANZ, CAM, LAM, SEA, SSA)^{2045}$

United States of America is always member of PFS coalitions. Another interesting development is that China and European Union are members of PFS coalitions only for the years 2025 and 2035, which has consequences for the improvement's volume in welfare and abatement levels of the farsighted stable coalitions (which will be discussed in the next section). Other interesting aspects are that Former Soviet Union is member of PFS coalitions from the year 2015 - 2045 and Japan and South Korea are members of PFS coalitions only in year 2045. The total number of countries varies from eleven[9] to fourteen[10] which

[9] 70 % of all regions for year 2005 and 2035.
[10] 88 % of all countries for year 2025.

means that in a "farsighted world" it is more likely that a lot of countries have economic incentives to join the environmental agreements like Kyoto protocol.
PFS coalitions vary for different time horizons. One does not expect that a stable IEA can function in this way. One needs more than farsightedness assumption for a long term stable IEA. It is crucial to have transfers and a cooperative behavior in order to maintain in long-term an IEA, but the mechanisms of implementing a cooperative attitude are difficult to build as they are undermined by free-riding.

4.6 Discussion on farsightedly stable coalition for different time horizons

In this section I discuss, the variation of farsightedly stable coalitions for different time horizons as function of variation of α's, β's, E's and Y's of coalition members. In order to analyze this question, an optimization problem is constructed. The following example is introduced for illustration; let take coalition $(USA, LAM, SEA, CHI, NAF, SSA)$ (I call it second coalition of 2005, $Coal^2_{2005}$) which is farsightedly stable in year 2005 (see Fig 4.1) but it is not farsightedly stable in year 2015. The coalition members are indexed for simplifying the presentation of optimization problem USA i=1, LAM i=2, SEA i=3, CHI i=4, NAF i=5, SSA i=6. Then I define $\alpha(i) = x(i)\alpha_{2005}(i)$, $\beta(i) = z(i)\beta_{2005}(i)$, $E(i) = v(i)E_{2005}(i)$, and $Y(i) = w(i)Y_{2005}(i)$ for each member i of coalition; *x, z, v, w* are the variables; the subscript 2005 indicates that α's, β's, E's and Y's from the year horizon 2005 are used as starting point (I will elaborate more on this question); $\pi_{atom}(i)$, $\pi_{coal}(i)$ profit (see equation 5.7) in atom structure, and when the above coalition is formed. The optimization problem is stated below:

$$\max[S_1 + S_2 + \sum_{i=1:6}[v(i) + w(i)] \tag{4.6}$$

where
$S_1 = \sum_{i=1:k_1}(1 - x(i)) + \sum_{i=1:(6-k_1)} x(i)$ for $1 \le k_1 \le 5$ and
$S_2 = \sum_{i=1:k_2}(1 - z(i)) + \sum_{i=1:(6-k_2)} z(i)$ for $1 \le k_2 \le 5$

$\pi_{coal}(i) - \pi_{atom}(i) > 0 \; \forall i \in Coal^2_{2005}$

For all (in)equalities below, I mean $\forall i \in Coal^2_{2005}$.
The lower bounds, **lb** and the upper bounds, **ub** of variables are introduced[11].

$lb_x(i) < x(i) < ub_x(i)$, $lb_z(i) < z(i) < ub_z(i)$
$lb_v(i) < v(i) < ub_v(i)$, $lb_w(i) < w(i) < ub_w(i) \; \forall i \in Coal^2_{2005}$
At the very beginning let's have a closer look at the objective function which maximizes the deviation of x, z, v, w from their starting point; let explain the construction of S_1 and S_2; in order to build S_1 and S_2, the members of coalition are divided in two groups; first group where each member satisfies $r_\alpha(i) < 1 \Rightarrow x(i) < 1$ (see footnote 11), then in order to maximize the deviation of x from his starting point 1, I maximize the sum of the amounts $(1 - x(i))$ (from 1 to k_1 that includes all the countries of first group), which implies the maximization of deviation $\alpha(i)$ from $\alpha(i)_{2005}$ for first group; second group with $r_\alpha(i) > 1 \Rightarrow x(i) > 1$, then again, in order to maximize the deviation of x from his starting point 1, I maximize sum of the amounts $x(i)$ (from 1 to (6-$k1$), that includes all the countries of first group, note also that maximizing $(x(i) - 1)$ is equivalent with maximizing $x(i)$, which implies the maximization of deviation $\alpha(i)$ from $\alpha(i)_{2005}$ for the second group. The S_2 is similarly built for variable z which is related to r_β. It is not necessary to introduce similar transformations for v, w as r_E and r_Y are always bigger than 1. Clearly maximizing the sum of x's (or (1-x)), z's (or (1-z)), v's and w's implies maximizing the variation of α's, β's, E's and Y's. The six constrains request that the coalition must be profitable and profitability is a necessary condition for being a farsightedly stable coalition[12] (but not sufficient). The

[11]The variable bounds explain also the construction of the objective function. Let's define $r_\alpha(i) = \alpha(i)_{2015}/\alpha(i)_{2005}$, then:
$if \;\; r_\alpha(i) > 1 \Rightarrow lb_x(i) = 1, \;\; ub_x(i) = r_\alpha(i)$
$if \;\; r_\alpha(i) < 1 \Rightarrow lb_x(i) = r_\alpha(i), \;\; ub_x(i) = 1$
$if \;\; r_\alpha(i) = 1 \Rightarrow lb_x(i) = 1, \;\; ub_x(i) = 1.$
The same clarifications can be made if I define $r_\beta(i) = \beta(i)_{2015}/\beta(i)_{2005}$, $r_E(i) = E(i)_{2015}/E(i)_{2005}$ and $r_Y(i) = Y(i)_{2015}/Y(i)_{2005}$.
[12]All farsightedly stable coalitions (which are found) are profitable too. I claim that checking farsighted stability (in stead of profitability) increases significantly the number of nonlinear constrains, and it is usually not necessary to check.

starting point is $x_0 = 1, z_0 = 1, v_0 = 1, w_0 = 1$, that is, I use the values of alpha's, beta's, E's and Y's from 2005 and this is a feasible starting point. The bounds simply imply that I allow the alpha's, beta's, E's and Y's to move in the interval from their value to 2005 to 2015[13] (or from value to 2015 to 2005, depending which value is bigger). As a conclusion the optimization process finds *the maximum deviation of sums of alpha's, beta's, E's and Y's* of the coalition members keeping *the coalition profitable in year 2015 (which implies giving a chance of being farsightedly stable coalition)* by letting alpha's beta's, E's and Y's *vary form their values in 2005 to 2015.*
The results of optimization process for coalition $(USA, LAM, SEA, CHI, NAF, SSA)$ are presented in Tables 4.5 and 4.6. The first column of Table 4.5 presents coalition-members, the next two columns are values of x's and z's that optimization process finds and the last four columns are the lower and upper bounds for x's and z's. The Table 4.6 is identical with Table 4.5, but presents variables v's and w's, that optimization process finds. The α's, β's and Y of each coalition-member (respectively variables x's, z's and w's in Tables 4.5 and 4.6) vary and and take the values of year 2015 (of their upper bounds). The E's (respectively the variables v's in Table 4.6) of each coalition member can take their value of 2015, except South East Asia (SEA). For keeping coalition profitable, *it is only necessary that SEA keeps emissions (respectively variable v for SEA) lower than the value of year 2015, namely lower than its upper bound*[14] (all other v's as well as x's, z's and w's can take the values of year 2015). The SEA is the country that increases his emissions and GDP (Y) more than any other coalition member from year 2005 to 2015. As a consequence, the cost of pollution abatement of SEA is increased also. Note that, the variation of emissions influences benefits and costs of a coalition member from pollution abatement; as increase (or decrease) of emissions causes the increase (or decrease) of the *abatement level* R[15] which influences directly the costs and benefits from pollution abatement; increase of GDP raises the cost from pollution abatement only. The same phenomena[16] happens when I consider coalitions $(ANZ, EEU, FSU, MDE, CAM, LAM, SAS, SEA, SIS)$, $(USA, WEU, CHI, NAF, SSA)$ of the year horizon 2025 (the results of optimization process are presented in Tables 4.7, 4.8, 4.9 and 4.10), and coalitions $(ANZ, EEU, FSU, MDE, CAM, LAM, SAS, SIS)$ of the year horizons 2035 (the results of optimization process are presented in Tables 4.11 and 4.12)[17]. The only highlight from the optimization problem is the following, a coalition remains profitable in the next year horizons if the emissions of only one country remains under his value of the latest year horizons. In order to investigate more on this point (why coalitions are varying from one year horizon to the next one) I change a bit the optimization problem that it is already introduced by *placing a different objective function (the bounds of variables are identical, so I do not rewrite them).* I put the sum of constrains as objective function:

$$\max \sum_{i}^{6} (\pi_{coal}(i) - \pi_{atom}(i)) \; \forall i \in Coal^2_{2005} \tag{4.7}$$

$$\pi_{coal}(i) - \pi_{atom}(i) > 0 \; \forall i \in Coal^2_{2005}$$

The optimization process (4.7) finds *the maximum satisfaction of the profitability constrains* keeping *the coalition profitable in year 2015* by letting alpha's, beta's, E's and Y's *vary form their values in 2005 to 2015.* The results are presented in Tables 4.13 and 4.14 which have the same structure as Tables 4.5 and 4.6. The new optimization problem requests that the coalition is kept as much profitable as possible,

The number of constrains for a coalition with six members, that are necessary to check only the internal farsighted stability are $2^6 - 7$ (all sub-coalitions of a farsightedly stable coalition with at least two members). Moreover, all profitable coalitions that I have checked are internally farsightedly stable. The size of a coalition does not vary too much from one time horizons to the next one. This implies that coalitions which are going to be discussed (which are farsightedly stable) must usually remain (but not always) externally and subcoalition farsightedly stable to the next time horizons.

[13]Note that if $r_\alpha(i) = \alpha(i)_{2015}/\alpha(i)_{2005} > 1 \Leftrightarrow \alpha(i)_{2015} > \alpha(i)_{2005} \;\; \forall \alpha(i) > 0$ and if $lb_x(i) = 1 \Leftrightarrow lb_\alpha(i) = \alpha_{2005}(i)$ as $\alpha(i) = x(i)\alpha_{2005}(i)$. Besides $lb_x(i) = r_\alpha(i) \Leftrightarrow ub_\alpha(i) = r_\alpha(i)\alpha_{2005}(i) = \alpha(i)_{2015}$ as $\alpha(i) = x(i)\alpha_{2005}(i)$. So the bounds on x's simply imply that if $\alpha(i)_{2015} > \alpha(i)_{2005}$ then $lb_\alpha(i) = \alpha_{2005}(i)$ and $ub_\alpha(i) = \alpha_{2015}(i)$. So all bounds guarantee that α's, β's, E's and Y's move from their value of 2005 to their value to 2015.

[14]The value of v that the optimization process finds and its upper bound are in bold letters.

[15]As emissions reductions for each country j of the six member coalition are $R(j) = \mathbf{E(j)}/(2\alpha(j)Y(j)) \sum_i^6 \beta(i)$.

[16]The first coalition $(CAN, EEU, CAM, SAS, SIS)$ of year 2005 can not be checked by optimization proceeding because it is also profitable in year 2015. The same is true for both coalitions of year 2015 $(CAN, EEU, FSU, CAM, LAM, SAS, SIS)$, $(USA, WEU, CHI, NAF, SSA)$ as well as for the second coalition $(USA, NAF, SSA)^{2035}$ of year 2035, which can not be checked by optimization proceeding because they are profitable in the following next year.

[17]That coalitions $(ANZ, EEU, FSU, MDE, CAM, LAM, SAS, SEA, SIS)$, $(USA, WEU, CHI, NAF, SSA)$ remain profitable at year 2035, it is necessary that FSU (form first coalition) and USA (from second coalition) keep their emissions levels lower than the levels of year 2035. That coalition $(ANZ, EEU, FSU, MDE, CAM, LAM, SAS, SIS)$ remains profitable in year 2045, it is necessary that FSU keeps its emissions level lower than the level of year 2045. Note that FSU and USA increase their emissions and GDP more than majority of countries of their coalitions.

and it realizes this aim in two ways; the first one, *by decreasing of betas (marginal benefits from pollution abatement)* for all coalition members except China (China can not decrease its beta as its lower bound is 1) which *keeps small the variation in marginal benefits (MB)* among coalition members from pollution abatement; the second one, *by not increasing the emissions* E (equivalently keeping the variables v constant at their lower bound 1) of participants of coalition. The similar trend (with some minor differences[18]) occurs when I discuss coalitions $(ANZ, EEU, FSU, MDE, CAM, LAM, SAS, SEA, SIS)$, $(USA, WEU, CHI, NAF, SSA)$ of the year horizon 2025 (the results of the optimization process are presented in Tables 4.15, 4.16, 4.17 and 4.18), and coalitions $(ANZ, EEU, FSU, MDE, CAM, LAM, SAS, SIS)$ of the year horizons 2035 (the results of optimization process are presented in Tables 4.19 and 4.20). There is no surprise that E and β's play the important role on keeping the coalitions profitable (and giving a chance of being farsightedly stable) in the next year horizons. I already noted that emissions E influence the benefits and costs from pollution abatement; the change of beta's influences environmental benefits and costs of coalition member from each-other in two directions: firstly, as variation of beta causes the change of abatement level of each coalition member which influences directly the benefits and costs[19], secondly as benefits of each coalition member is a function of his beta[20]. The Y (GDP) and α's influence only the costs (but not the benefits), that is why they play a minor role on maintaining the coalitions profitable from one year horizon to the next one.
The results of the optimization (4.7) are presented also in Figure 4.2, 4.3, 4.4, 4.5 and 4.6. The relative change intervals[21] of alphas and betas are introduced in Figure 4.2. In the y-axis are alpha values (cost parameter, unitless) and in the x-axis are beta values (MB from pollution abatements in dollars for tonnes of carbon). If there is a circle for a certain country (for example, example USA) then the alpha and beta (of USA) can change from their value of year 2005 to the value of the year 2015 (or from year 2015 to year 2005 if the value of year 2015 is smaller than the value of year 2005) and the coalition $(USA, LAM, SEA, CHI, NAF, SSA)$ remains profitable (*which implies giving a chance of being farsightedly stable coalition*). Moreover, the diameter of circle which is parallel to y-axis represents the relative interval change of alpha and the diameter of circle which is parallel to x-axis represents the relative interval change of beta. If there is only a line (in stead of a circle) parallel to y-axis for a certain country (for example, example China, CHI) it indicates that for maintaining the coalition profitable, it is compulsory that only alpha (of China) changes its value[22](beta not). As alphas and betas vary from their lower bounds to their upper bounds, or they do not vary at all I receive circles with diameter one or lines with length one. The same explanation can be carried out for Figure 4.2 where relative changes for emissions E (in billion metric tonnes of carbon) and Y (GDP, in billion US dollars) are presented. There are only lines with length one (no circles) in Figure 4.2 as emissions E of every participant of coalition do not change.
The Figure 4.4 introduces the absolute change intervals of alphas and betas. The description is identical for Figure 4.2 but in stead of circles, there are ellipses as absolute change intervals of alphas and betas are different. The same description can be carried out for Figure 4.4 where results for emissions E and Y are presented. There are only lines (no ellipses) in Figure 4.4 as emissions E of every coalition member does not change.
The Figure 4.6 presents the absolute variation intervals of alphas (x-axis), betas (y-axis) and Y (GDP, z-axis) simultaneously. There is an ellipsoid for every coalition member except China which has an ellipse in a plane parallel to zy-plan, as MB (beta) of China does not vary.
As a conclusion the profitability condition of farsighted stable coalitions (and as consequence the farsighted stability) can be maintained by changing the emissions of one coalition member. In order to have robust profitable coalitions it is necessary that the disproportional variations on marginal benefits from pollution abatement among coalition members are prevented, and emissions are not increased. Nevertheless, emissions and marginal benefits from pollution abatement are controlled by rate of economic growth of each country and cannot be influenced.

[18]For the coalition $(ANZ, EEU, FSU, MDE, CAM, LAM, SAS, SEA, SIS)$, FSU decreases its beta, but it does not reach its lower bound while ANZ increases its GDP (Y) but not up to its upper bound (similar phenomena occurs with other coalitions).

[19]As emissions reductions for each country j of the six member coalition are $R(j) = E(j)/(2\alpha(j)Y(j))\sum_i^6 \beta(i)$.

[20]As benefits of each country i is $B(i) = \beta(i)\sum_j^n R(j)E(j)$ where n is the total number of countries.

[21]The relative change of alpha is equal $(\alpha op - lb(\alpha))/(ub(\alpha) - lb(\alpha))$ where α_{op} is the value that optimization finds and $lb(\alpha), ub(\alpha)$ are lower and upper bounds of alpha. Similarly, one speaks for the relative changes of beta, E and Y.

[22]If there is only a line parallel to x-axis for a certain country it signifies that for maintaining coalition profitable, it is necessary that only beta changes, or in case that there is only a point for a certain country it indicates that for maintaining the coalition profitable, it is compulsory that neither alpha nor beta changes (but the two last cases do not occur when considering this coalition).

4.7 Conclusion

The paper analyzes the problem of evolution of farsightedly stable coalition for different time horizons. The FUND model supplies the cost-benefit functions of pollution abatement which govern the results. Clearly the profits functions of pollution abatement consider only economic incentives.
The number of farsightedly stable coalitions is big especially for last time horizons, this implies that there are a lot of countries which have economic incentives to join international environmental agreements like Kyoto protocol in a "farsighted world". The farsightedly stable coalitions are refined further to preferred farsightedly stable coalitions. There are two preferred farsightedly stable coalitions for each time horizons which include more than two thirds (from eleven to fourteen) of sixteen world regions, and they improve substantially the welfare and abatement levels compare to atom structure.
The farsighted stability is fragile with respect to small variations in parameters and circumstances. In order to have robust farsightedly stable coalitions for different time horizons, one needs to keep the emissions of each coalition member and the variation of marginal benefits from pollution abatement among coalition members as low as possible. However, emissions and marginal benefits from pollution abatement are determined by rate of economic growth of each country and cannot be controlled. Furthermore, the members and size of farsightedly stable coalitions are very sensible to the emission variation of certain coalition members from one year horizon to the future one. Then, it follows that farsightedly stable coalitions cannot be sustained for long terms, which implies that the "selfish farsighted world" can assure only temporary big international coalitions. This appeals for further research that considers not only economic incentives but also commitment to environmental protection as well as a more cooperative approach, which has to include side transfers.

Acknowledgment

I am grateful to Richard Tol for his comments and suggestions.

Table 4.1: Abatement cost parameter α (unitless) for all time horizons. Source: FUND

	2005	2015	2025	2035	2045
USA	1.5155	1.5194	1.5229	1.5236	1.5241
CAN	1.5168	1.5205	1.5244	1.525	1.5253
WEU	1.568	1.568	1.5646	1.5607	1.559
JPK	1.5628	1.5591	1.568	1.568	1.568
ANZ	1.5106	1.5149	1.5196	1.5215	1.5229
EEU	1.4652	1.4733	1.4777	1.4813	1.4842
FSU	1.3818	1.3839	1.3979	1.4053	1.4107
MDE	1.4347	1.44	1.4528	1.4643	1.473
CAM	1.4864	1.4911	1.4985	1.5039	1.5084
LAM	1.5137	1.5161	1.5216	1.5256	1.5291
SAS	1.4366	1.4455	1.458	1.4674	1.4753
SEA	1.4849	1.4881	1.4967	1.5033	1.5088
CHI	1.4444	1.4589	1.4666	1.473	1.4785
NAF	1.46	1.4706	1.4853	1.4955	1.5029
SSA	1.4592	1.4718	1.4865	1.4964	1.5039
SIS	1.4346	1.4387	1.4498	1.4579	1.4648

Table 4.2: Marginal damage costs of carbon dioxide emissions β, in dollars per tonne of carbon for all time horizons. Source: FUND

	2005	2015	2025	2035	2045
USA	2.2	1.98	1.76	1.54	1.33
CAN	0.09	0.1	0.1	0.1	0.09
WEU	3.16	3.05	2.86	2.62	2.35
JPK	-1.42	-0.86	-0.44	-0.13	0.07
ANZ	-0.05	0	0.03	0.06	0.07
EEU	0.1	0.11	0.11	0.11	0.1
FSU	1.27	1.1	0.95	0.82	0.71
MDE	0.05	0.17	0.26	0.31	0.33
CAM	0.07	0.1	0.12	0.13	0.13
LAM	0.27	0.24	0.22	0.19	0.17
SAS	0.36	0.38	0.39	0.39	0.37
SEA	0.73	0.69	0.64	0.57	0.51
CHI	4.36	5.21	5.56	5.54	5.28
NAF	0.97	0.83	0.71	0.6	0.51
SSA	1.07	0.82	0.64	0.51	0.41
SIS	0.06	0.07	0.07	0.08	0.07

Table 4.3: Carbon dioxide emissions E in billion metric tonnes of carbon, for all time horizons. Source: FUND

	2005	2015	2025	2035	2045
USA	1647	1816	1926	2157	2402
CAN	124	139	146	164	183
WEU	762	810	889	999	1111
JPK	525	610	676	761	846
ANZ	79	92	102	115	128
EEU	177	201	262	336	414
FSU	811	1093	1339	1702	2093
MDE	424	551	690	823	976
CAM	115	137	160	188	222
LAM	223	266	310	365	429
SAS	559	756	883	1039	1224
SEA	334	492	575	676	795
CHI	1431	1798	2228	2764	3428
NAF	101	120	139	163	192
SSA	145	169	196	231	271
SIS	38	49	58	69	82

Table 4.4: Gross domestic product Y in billion US dollar for all time horizons. Source: FUND

	2005	2015	2025	2035	2045
USA	10399	13372	16199	19089	22029
CAN	807	1054	1277	1506	1739
WEU	12575	15569	18781	22114	25495
JPK	8528	11130	14408	17589	20794
ANZ	446	606	785	960	1136
EEU	407	544	780	1085	1429
FSU	629	872	1249	1735	2281
MDE	614	871	1335	1940	2707
CAM	388	524	733	996	1332
LAM	1351	1804	2519	3414	4554
SAS	831	1296	1858	2587	3545
SEA	1094	1770	2535	3526	4826
CHI	2376	3795	5420	7619	10560
NAF	213	309	481	710	1005
SSA	302	445	694	1026	1456
SIS	55	76	107	146	196

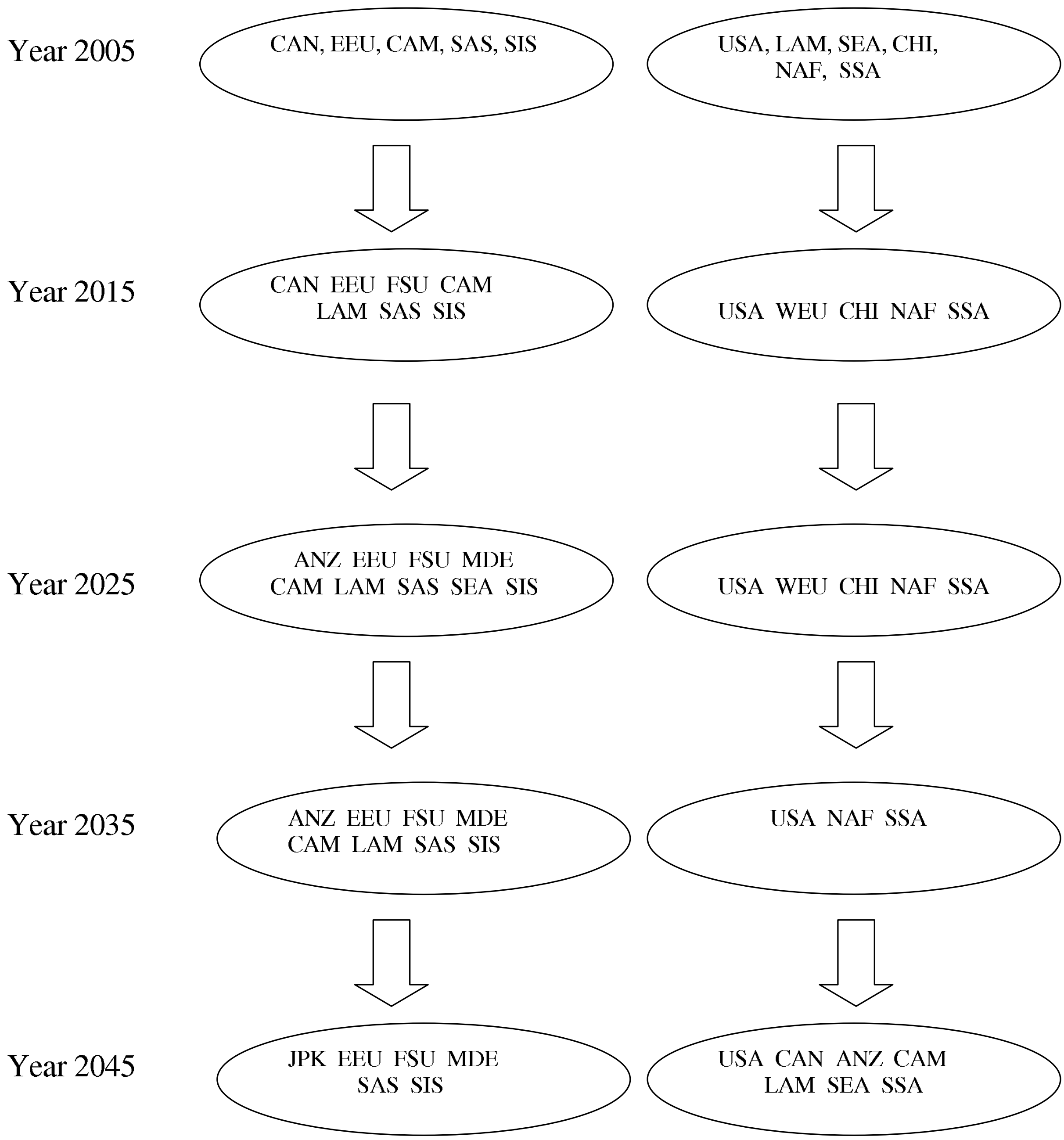

Figure 4.1: Farsighted stable coalitions for different time horizons.

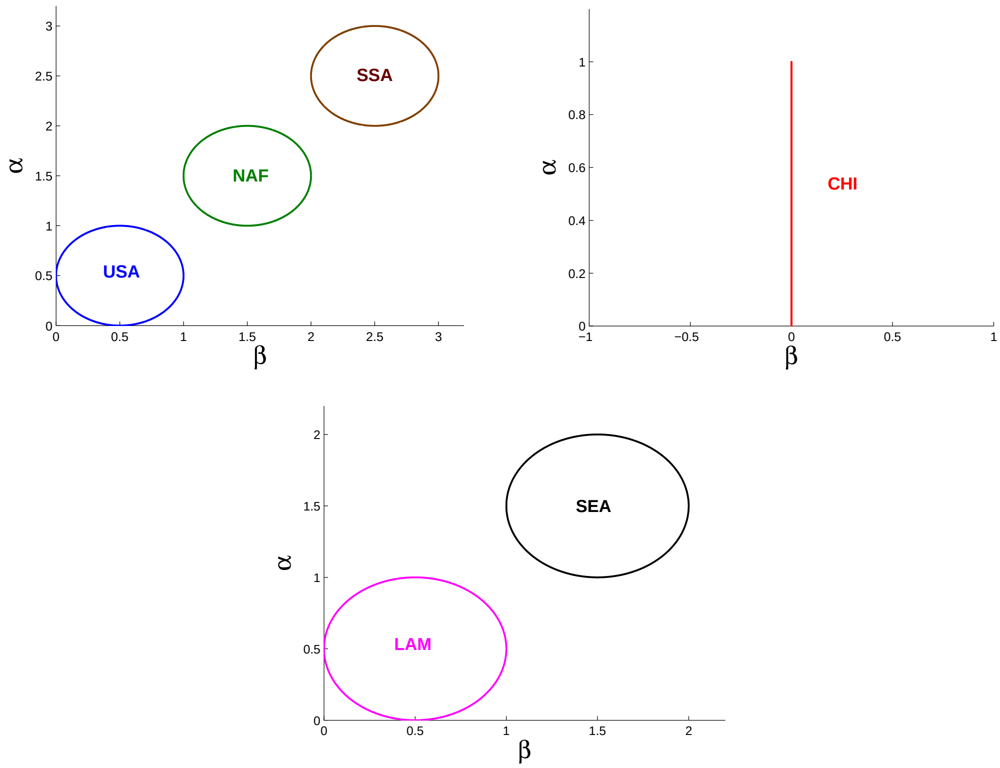

Figure 4.2: The relative change intervals of alphas and betas of each coalition-member that give a chance the coalition coalition (USA, LAM, SEA, CHI, NAF, SSA) of being FS coalitions, *second optimization problem*.

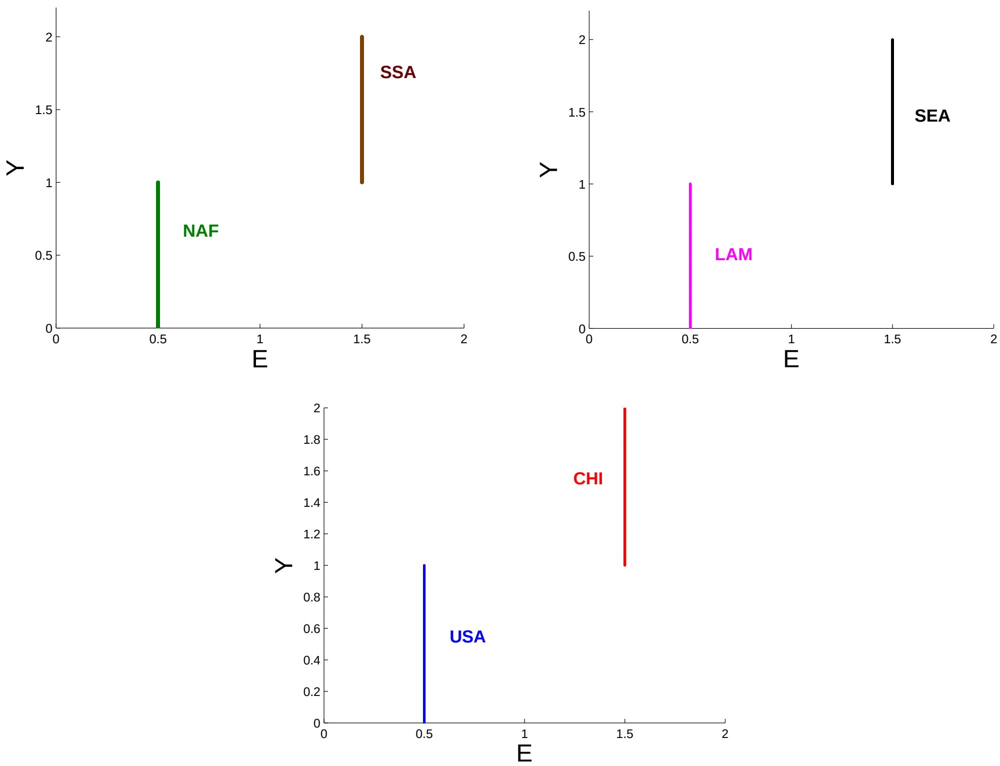

Figure 4.3: The relative change intervals of E and Y (GDP) of each coalition-member that give a chance to the coalition (USA, LAM, SEA, CHI, NAF, SSA) of being FS coalitions, *second optimization problem.*

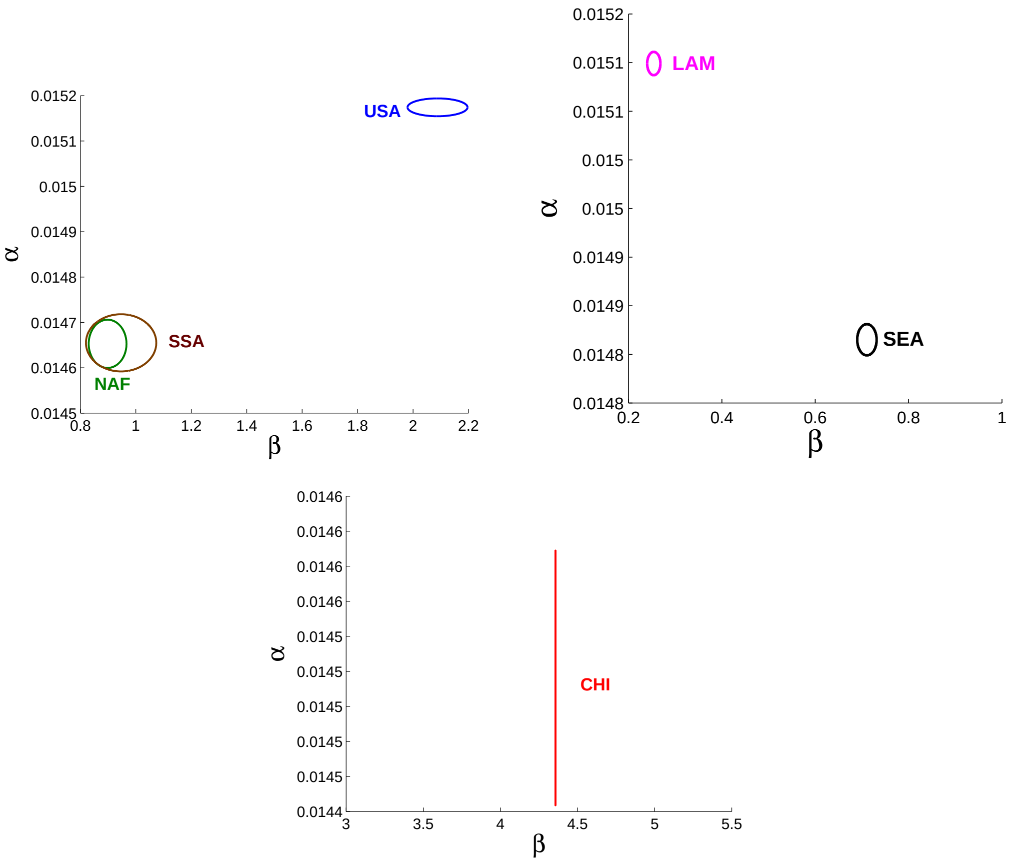

Figure 4.4: The absolute change intervals of alphas and betas of each coalition-member that give a chance to the coalition (USA, LAM, SEA, CHI, NAF, SSA) of being FS coalitions, *second optimization problem.*

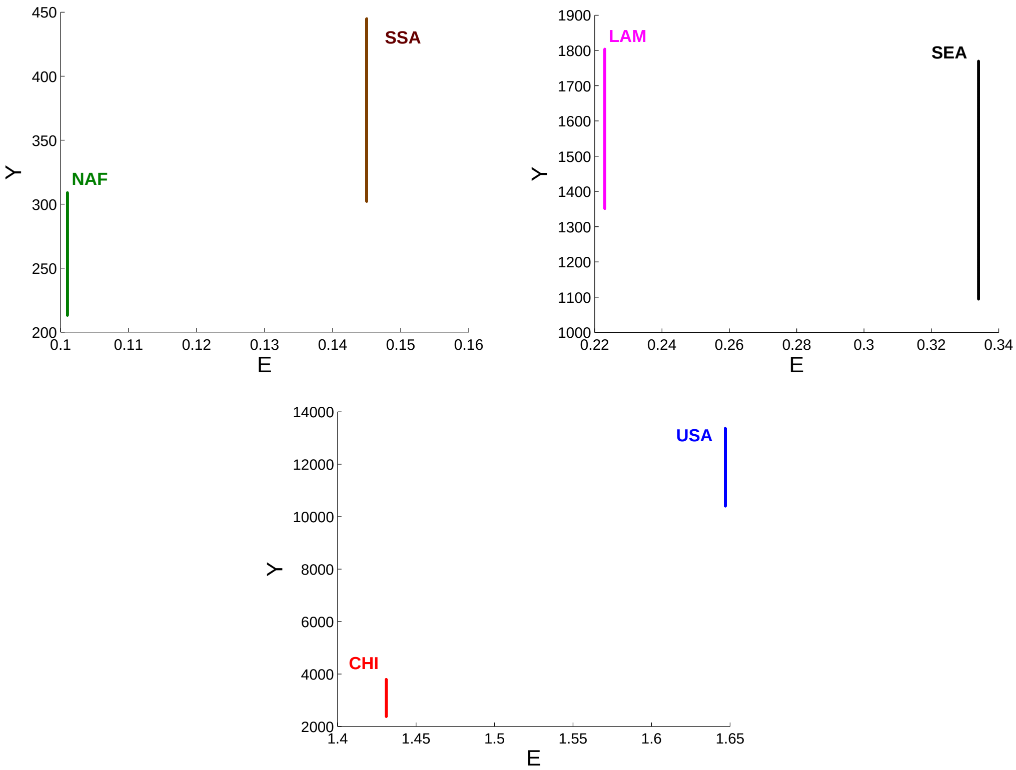

Figure 4.5: The absolute change intervals of E and Y (GDP) of each coalition-member that give a chance to the coalition (USA, LAM, SEA, CHI, NAF, SSA) of being FS coalitions, *second optimization problem.*

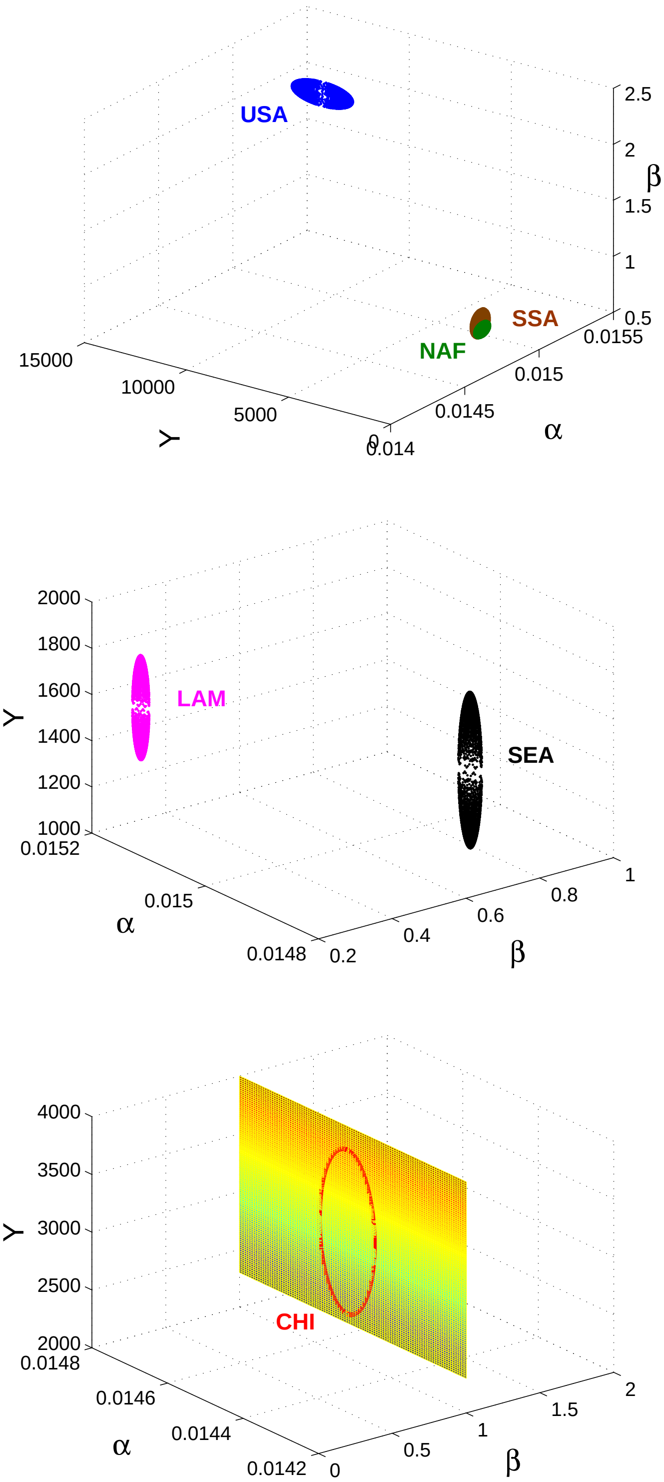

Figure 4.6: The absolute change intervals of alphas and betas and Y (GDP) of each coalition-member that give a chance to the coalition (USA, LAM, SEA, CHI, NAF, SSA) of being FS coalitions, *second optimization problem*.

Table 4.5: Second coalition 2005, first optimization problem, variables x and z.

Coalition	x	z	lb_x	ub_x	lb_z	ub_z
USA	1.0026	0.9014	1	1.0026	0.9014	1
LAM	1.0016	0.8942	1	1.0016	0.8942	1
SEA	1.0022	0.9431	1	1.0022	0.9431	1
CHI	1.0101	1.1958	1	1.0101	1	1.1958
NAF	1.0073	0.859	1	1.0073	0.859	1
SSA	1.0086	0.7637	1	1.0086	0.7637	1

Table 4.6: Second coalition 2005, first optimization problem, variables v and w.

Coalition	v	w	lb_v	ub_v	lb_w	ub_w
USA	1.1026	1.2859	1	1.1026	1	1.2859
LAM	1.1928	1.3353	1	1.1928	1	1.3353
SEA	**1.3841**	1.6179	1	**1.4731**	1	1.6179
CHI	1.2565	1.5972	1	1.2565	1	1.5972
NAF	1.1881	1.4507	1	1.1881	1	1.4507
SSA	1.1655	1.4735	1	1.1655	1	1.4735

Table 4.7: First coalition 2025, first optimization problem, variables x and z.

Coalition	x	z	lb_x	ub_x	lb_z	ub_z
ANZ	1.0013	2	1	1.0013	1	2
EEU	1.0024	1	1	1.0024	1	1
FSU	1.0053	0.8632	1	1.0053	0.8632	1
MDE	1.0039	1.1923	1	1.0079	1	1.1923
CAM	1.0036	1.0833	1	1.0036	1	1.0833
LAM	1.0026	0.8636	1	1.0026	0.8636	1
SAS	1	1	1	1.0064	1	1
SEA	1.0044	0.8906	1	1.0044	0.8906	1
SIS	1.0056	1.1429	1	1.0056	1	1.1429

Table 4.8: First coalition 2025, first optimization problem, variables v and w.

Coalition	v	w	lb_v	ub_v	lb_w	ub_w
ANZ	1.1275	1.2229	1	1.1275	1	1.2229
EEU	1.2824	1.391	1	1.2824	1	1.391
FSU	**1.0796**	1.3891	1	**1.2711**	1	1.3891
MDE	1.1928	1.4532	1	1.1928	1	1.4532
CAM	1.175	1.3588	1	1.175	1	1.3588
LAM	1.1774	1.3553	1	1.1774	1	1.3553
SAS	1.1767	1.3924	1	1.1767	1	1.3924
SEA	1.1757	1.3909	1	1.1757	1	1.3909
SIS	1.1897	1.3645	1	1.1897	1	1.3645

Table 4.9: Second coalition 2025, first optimization problem, variables x and z.

Coalition	x	z	lb_x	ub_x	lb_z	ub_z
USA	1.0005	0.875	1	1.0005	0.875	1
WEU	0.9975	0.9161	0.9975	1	0.9161	1
CHI	1.0044	0.9964	1	1.0044	0.9964	1
NAF	1.0069	0.8451	1	1.0069	0.8451	1
SSA	1.0067	0.7969	1	1.0067	0.7969	1

Table 4.10: Second coalition 2025, first optimization problem, variables v and w.

Coalition	v	w	lb_v	ub_v	lb_w	ub_w
USA	**1.1167**	1.1784	1	**1.1199**	1	1.1784
WEU	1.1237	1.1775	1	1.1237	1	1.1775
CHI	1.2406	1.4057	1	1.2406	1	1.4057
NAF	1.1727	1.4761	1	1.1727	1	1.4761
SSA	1.1786	1.4784	1	1.1786	1	1.4784

Table 4.11: First coalition 2035, first optimization problem, variables x and z.

Coalition	x	z	lb_x	ub_x	lb_z	ub_z
ANZ	1.0009	1.1667	1	1.0009	1	1.1667
EEU	1.002	0.9091	1	1.002	0.9091	1
FSU	1.0038	0.8659	1	1.0038	0.8659	1
MDE	1.0059	1.0645	1	1.0059	1	1.0645
CAM	1.003	1	1	1.003	1	1
LAM	1.0023	0.8947	1	1.0023	0.8947	1
SAS	1.0054	0.9487	1	1.0054	0.9487	1
SIS	1.0047	0.875	1	1.0047	0.875	1

Table 4.12: First coalition 2035, first optimization problem, variables v and w.

Coalition	v	w	lb_v	ub_v	lb_w	ub_w
ANZ	1.113	1.1833	1	1.113	1	1.1833
EEU	1.2321	1.3171	1	1.2321	1	1.3171
FSU	**1.0827**	1.3147	1	**1.2297**	1	1.3147
MDE	1.1859	1.3954	1	1.1859	1	1.3954
CAM	1.1809	1.3373	1	1.1809	1	1.3373
LAM	1.1753	1.3339	1	1.1753	1	1.3339
SAS	1.1781	1.3703	1	1.1781	1	1.3703
SIS	1.1884	1.3425	1	1.1884	1	1.3425

Table 4.13: Second coalition 2005, second optimization problem, variables x and z.

Coalition	x	z	lb_x	ub_x	lb_z	ub_z
USA	1.0026	0.9014	1	1.0026	0.9014	1
LAM	1.0016	0.8942	1	1.0016	0.8942	1
SEA	1.0022	0.9431	1	1.0022	0.9431	1
CHI	1.0101	1	1	1.0101	1	1.1958
NAF	1.0073	0.859	1	1.0073	0.859	1
SSA	1.0086	0.7637	1	1.0086	0.7637	1

Table 4.14: Second coalition 2005, second optimization problem, variables v and w.

Coalition	v	w	lb_v	ub_v	lb_w	ub_w
USA	1	1.2859	1	1.1026	1	1.2859
LAM	1	1.3353	1	1.1928	1	1.3353
SEA	1	1.6179	1	1.4731	1	1.6179
CHI	1	1.5972	1	1.2565	1	1.5972
NAF	1	1.4507	1	1.1881	1	1.4507
SSA	1	1.4735	1	1.1655	1	1.4735

Table 4.15: First coalition 2025, second optimization problem, variables x and z.

Coalition	x	z	lb_x	ub_x	lb_z	ub_z
ANZ	1.0013	1	1	1.0013	1	2
EEU	1.0024	1	1	1.0024	1	1
FSU	1.0053	**0.9421**	1	1.0053	**0.8632**	1
MDE	1.0079	1	1	1.0079	1	1.1923
CAM	1.0036	1	1	1.0036	1	1.0833
LAM	1.0026	0.8636	1	1.0026	0.8636	1
SAS	1.0064	1	1	1.0064	1	1
SEA	1.0044	0.8906	1	1.0044	0.8906	1
SIS	1.0056	1	1	1.0056	1	1.1429

Table 4.16: First coalition 2025, second optimization problem, variables v and w.

Coalition	v	w	lb_v	ub_v	lb_w	ub_w
ANZ	1	**1.1750**	1	**1.1275**	1	1.2229
EEU	1	1.391	1	1.2824	1	1.391
FSU	1	1.3891	1	1.2711	1	1.3891
MDE	1	1.4532	1	1.1928	1	1.4532
CAM	1	1.3588	1	1.175	1	1.3588
LAM	1	1.3553	1	1.1774	1	1.3553
SAS	1	1.3924	1	1.1767	1	1.3924
SEA	1	1.3909	1	1.1757	1	1.3909
SIS	1	1.3645	1	1.1897	1	1.3645

Table 4.17: Second coalition 2025, second optimization problem, variables x and z.

Coalition	x	z	lb_x	ub_x	lb_z	ub_z
USA	1.0005	**1**	1	1.0005	**0.875**	1
WEU	1	0.9161	0.9975	1	0.9161	1
CHI	1.002	0.9964	1	1.0044	0.9964	1
NAF	1.0069	0.8451	1	1.0069	0.8451	1
SSA	1.0067	0.7969	1	1.0067	0.7969	1

Table 4.18: Second coalition 2025, second optimization problem, variables v and w.

Coalition	v	w	lb_v	ub_v	lb_w	ub_w
USA	1	1.1784	1	1.1199	1	1.1784
WEU	1	1.1775	1	1.1237	1	1.1775
CHI	1.0048	**1.3994**	1	1.2406	1	**1.4057**
NAF	1	1.4761	1	1.1727	1	1.4761
SSA	1	1.4784	1	1.1786	1	1.4784

Table 4.19: First coalition 2035, second optimization problem, variables x and z.

Coalition	x	z	lb_x	ub_x	lb_z	ub_z
ANZ	1.0009	1	1	1.0009	1	1.1667
EEU	1.002	0.9091	1	1.002	0.9091	1
FSU	1.0038	**0.9591**	1	1.0038	**0.8659**	1
MDE	1.0059	1	1	1.0059	1	1.0645
CAM	1.003	1	1	1.003	1	1
LAM	1.0023	0.8947	1	1.0023	0.8947	1
SAS	1.0054	0.9487	1	1.0054	0.9487	1
SIS	1.0047	0.875	1	1.0047	0.875	1

Table 4.20: First coalition 2035, second optimization problem, variables v and w.

Coalition	v	w	lb_v	ub_v	lb_w	ub_w
ANZ	1	**1.1582**	1	1.113	1	**1.1833**
EEU	1	1.3171	1	1.2321	1	1.3171
FSU	1	1.3147	1	1.2297	1	1.3147
MDE	1	1.3954	1	1.1859	1	1.3954
CAM	1	1.3373	1	1.1809	1	1.3373
LAM	1	1.3339	1	1.1753	1	1.3339
SAS	1	1.3703	1	1.1781	1	1.3703
SIS	1	1.3425	1	1.1884	1	1.3425

4.8 Appendix

4.8.1 Numerical comparison between different coalition structure for different time horizons

As it is expected the preferred farsightedly stable (PFS) coalitions improve substantially the welfare (*or profit*) and abatement levels[23] in comparison to atom structure[24], and the grand coalitions improve significantly the welfare and abatement levels in comparison to PFS coalitions (and atom structure too)[25].
The PFS coalitions improve the welfare (and abatement level) until 2025 as European Union and China are members of PFS coalitions. Then it decreases again until 2045 when European Union and China are not members any longer, see Fig 4.7 (see Fig 4.8). The profit of grand coalition (and atom structure, see Fig 4.11) increases until 2035, then it decreases until year 2045, see Fig 4.9. On the other side, the abatement of grand coalition (and atom structure, see Fig 4.12) decreases constantly all the time, see Fig 4.10. My claim is that decreasing emissions becomes more expensive from year to year.
The grand coalitions, PFS coalitions and atom structure improve the abatement levels for different time horizons, 2005, 2025 and 2045. China, Former Soviet Union and USA have economic incentives for reducing the carbon dioxide emissions (by around $80-90\%$) (for atom structure see Fig 4.13, 4.14 and 4.15, for farsighted stable coalitions see Fig 4.16, 4.17 and 4.18, for grand coalitions see Fig 4.19, 4.20 and 4.21). Besides, the Former Soviet Union has a higher economic incentive to lower carbon dioxide emissions. South Asia and Middle East have bigger economic incentives to decrease carbon dioxide emissions in grand coalition in comparison to atom structure.
The welfare distribution, when two PFS coalitions (also true for grand coalition and atom structure) are formed (for different time horizons, 2005, 2025 and 2045) shows that China, Former Soviet Union and USA receive around the half of all profits, but they contribute to $80-90\%$ of all emissions reductions (for atom structure see Fig 4.22, 4.23 and 4.24, for farsighted stable coalitions see Fig 4.25, 4.26 and 4.27, for grand coalitions see Fig 4.28, 4.29 and 4.30). It is sometimes possible for above countries to improve those disproportionateness (between abatement levels and profits) by joining (FSU joins PFS coalitions after year 2005) or leaving (China and Western European Union leave the PFS coalitions after year 2025) the PFS coalitions. The biggest winner remains always European Union[26] and the biggest loser is Former Soviet Union[27]. Moreover, the loss of Former Soviet Union is increasing. Another big loser (only for years 2005 and 2015) is Japan[28]. Only for year 2045, it is possible for Japan to realize some profits by joining the PFS coalitions. A big loser is China too, it contributes strongly in decreasing of abatement levels but her welfare increases in a small amount.
Summing up the results, I reinforce the conclusion that it is impossible to imagine an IEA without participation of countries like Western European Union, USA, China and Soviet Union. As only economic incentives are considered, a picture that is not realistic is received. European Union is not a member of farsightedly coalitions until 2025 which contradicts the reality. This occurs because I do not consider any commitment to environmental protection, and perhaps the cost of environmental protection is too high[29]. The above numerical comparison is an appealing point that cooperative attitudes and transfers

[23] As the numerical results depend highly on assumptions of FUND model, one should take *the numerical comparison with carefulness*

[24] The preferred farsightedly stable coalitions improve the welfare (and abatement levels from 2.6 times for year 2045 to 5 times for year 2025) substantially in comparison to atom structure for all the years, from around 55 % for year 2045 to 2.4 times more for the year 2035. Even so, the rate of welfare improvement (and abatement levels) decreases as China and European Union are not member of farsightedly stable coalition for the years 2035 and 2045.

[25] The welfare "gap" (and abatement "gap") between atom structure and grand coalitions remains more or less constant for all years. The grand coalition improves the welfare by more than a factor 4 (and abatement level by a factor of 14-15) in comparison to atom structure. The grand coalition increases the welfare (and abatement levels) in comparison to farsightedly stable coalitions for all years. As it is expected the welfare "gap" (and abatement "gap") between grand coalition and farsightedly stable coalitions is smaller when China and European Union are members of farsightedly stable coalition (for years 2035 and 2045).

[26] Western European Union reduces its emissions less than 2% but it receives $28-38\%$ of profits (taking the average of welfare and abatement levels of each coalition structure on different time horizons).

[27] Former Soviet Union decreases his emissions by $18-38\%$, but his welfare varies from -20% to 8% (taking the average of welfare and abatement levels of each coalition structure on different time horizons)

[28] Japan decreases its emissions by $0.02-0.4\%$, but her welfare decreases by $6-8\%$ (taking the average of welfare and abatement levels of each coalition structure on different time horizons)

[29] On the contrary, in a cooperative approach, WEU is a key player (Only year 2005 is checked, when WEU is not a member of farsightedly stable coalitions), but the cooperative attitude is out of scope of this paper. WEU is always a member of coalitions (CHI, FSU and USA too) which achieve the maximum welfare improvement, although they are not stable. "Only a cooperative behavior", which determines also how to distribute the welfare, can make the above coalitions

are essential in order to have a stable IEA. Besides, FUND suggests that the transfers should flow mostly from European Union (or in a smaller amount from USA) to Former Soviet Union or China. A "farsightedly non-cooperative world" shifts the costs of environmental protection to China and Former Soviet Union (sometimes to South Asia and Middle East) while the profits are reallocated mainly to European Union and USA.

stable. As it is known, enforcing a cooperative behavior is difficult because of free-riding.

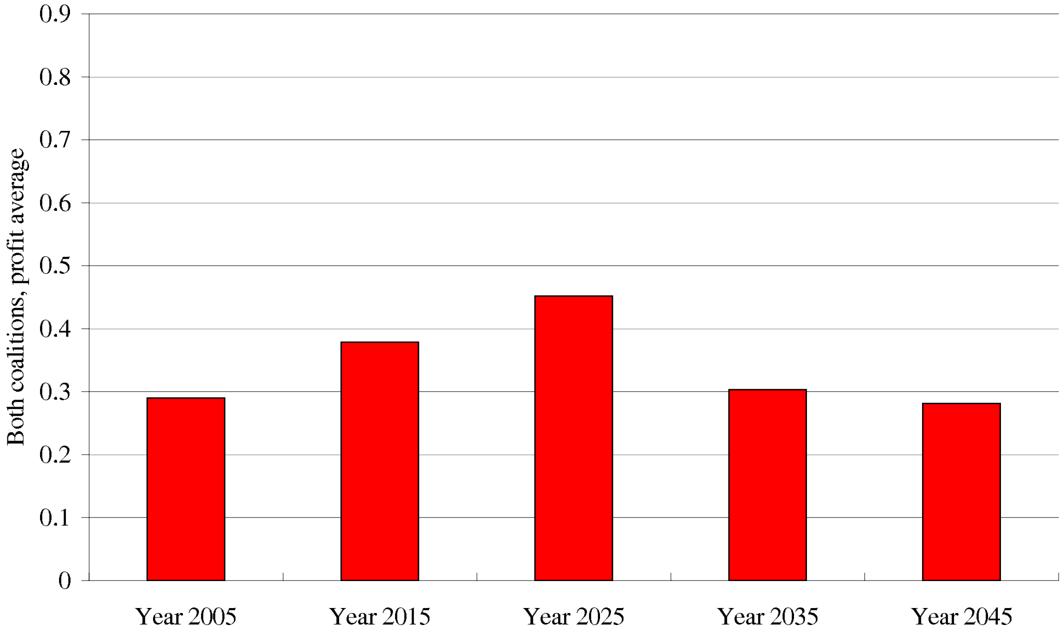

Figure 4.7: Average profit when two farsighted stable coalitions are formed, different time horizons.

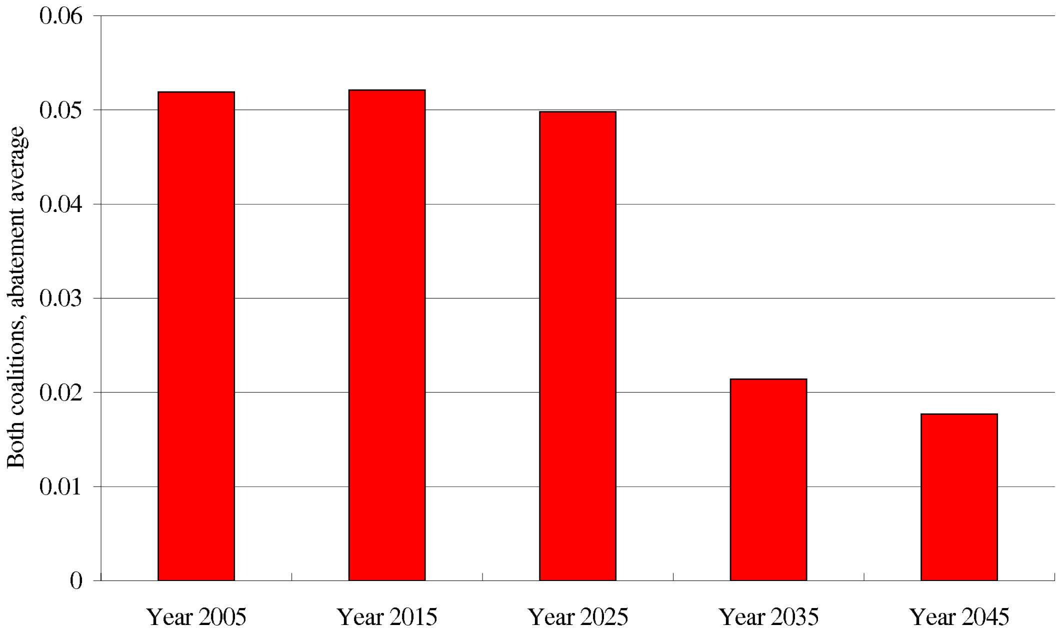

Figure 4.8: Average abatement when two farsighted stable coalitions are formed, different time horizons.

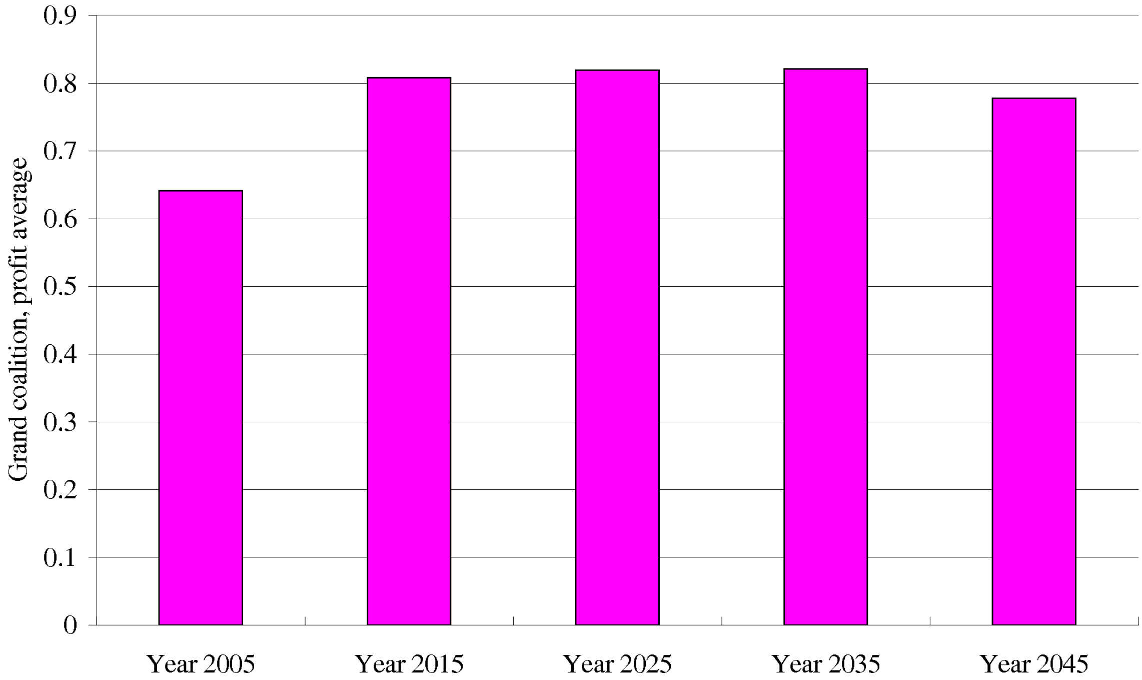

Figure 4.9: Average profit for grand coalition, different time horizons.

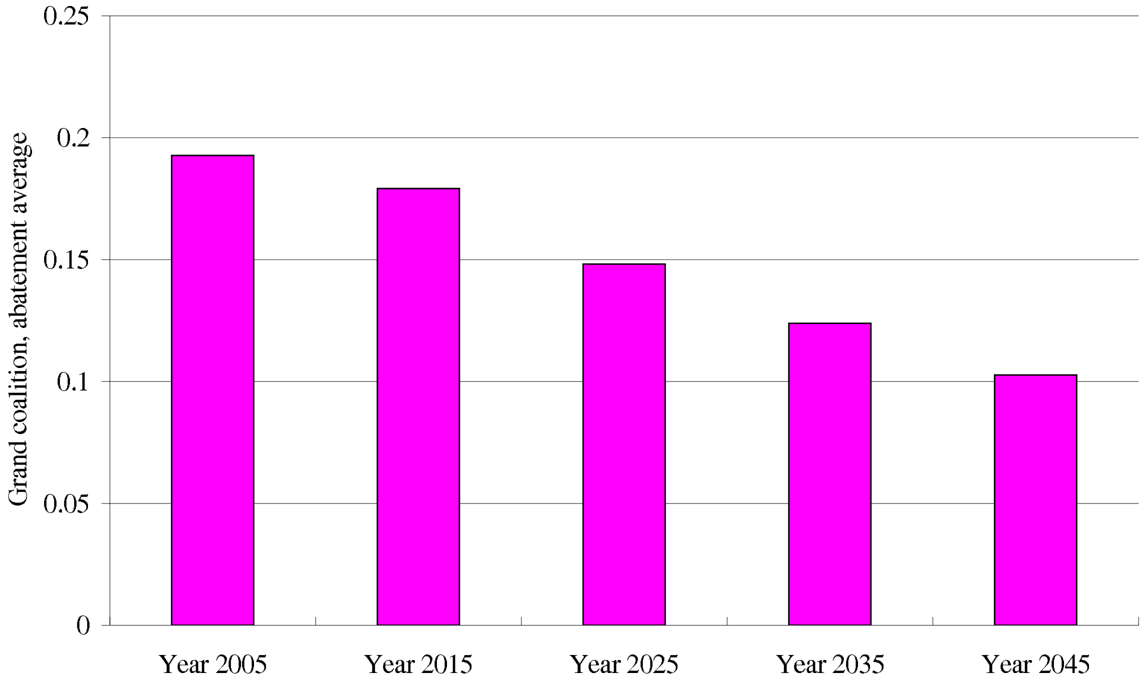

Figure 4.10: Average abatement for grand coalition, different time horizons.

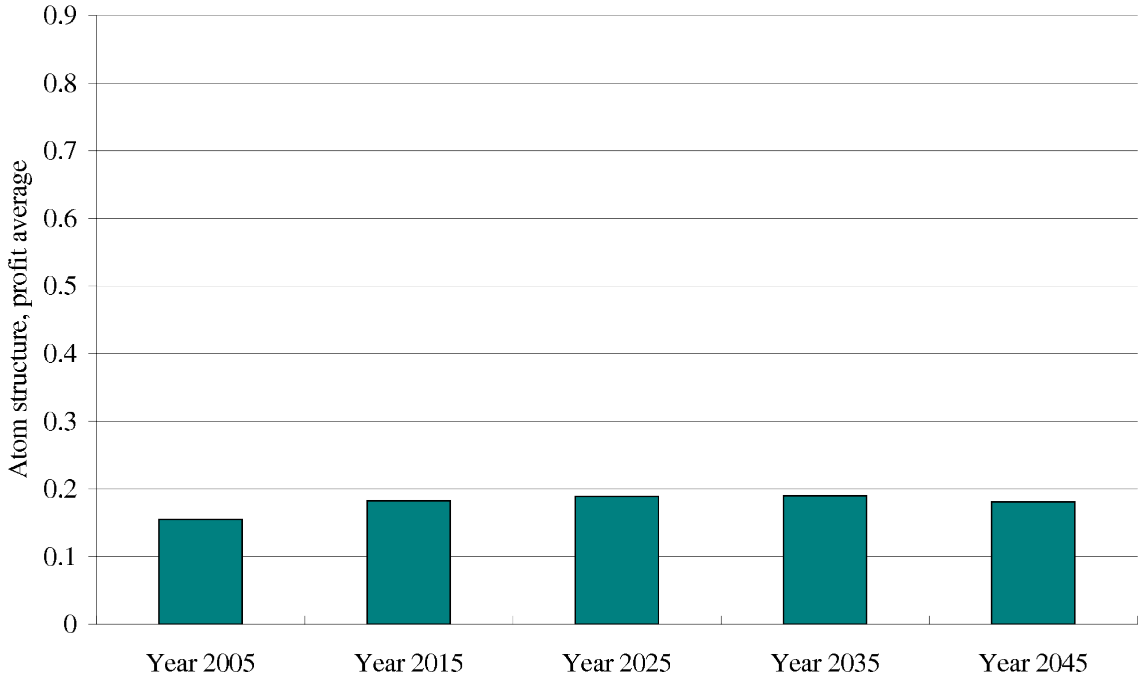

Figure 4.11: Average profit for atom structure, different time horizons.

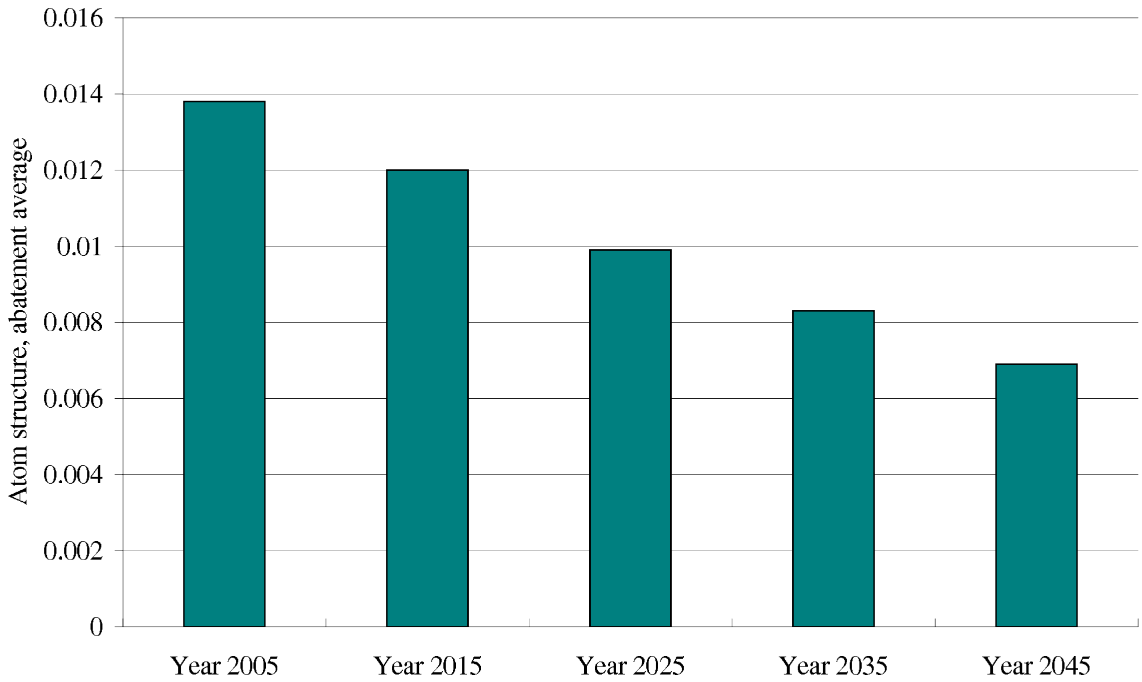

Figure 4.12: Average abatement for atom structure, different time horizons.

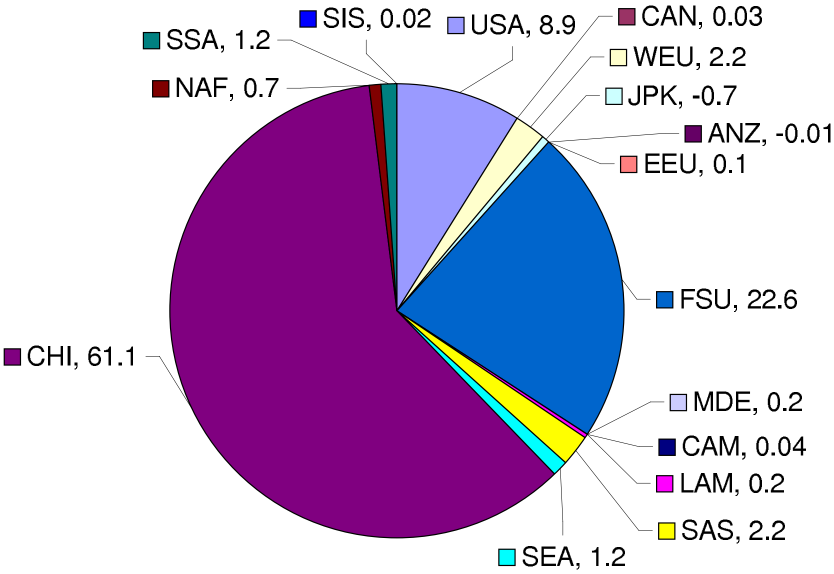

Figure 4.13: The share of abatement level for each region (in percentage) in atom structure, year 2005.

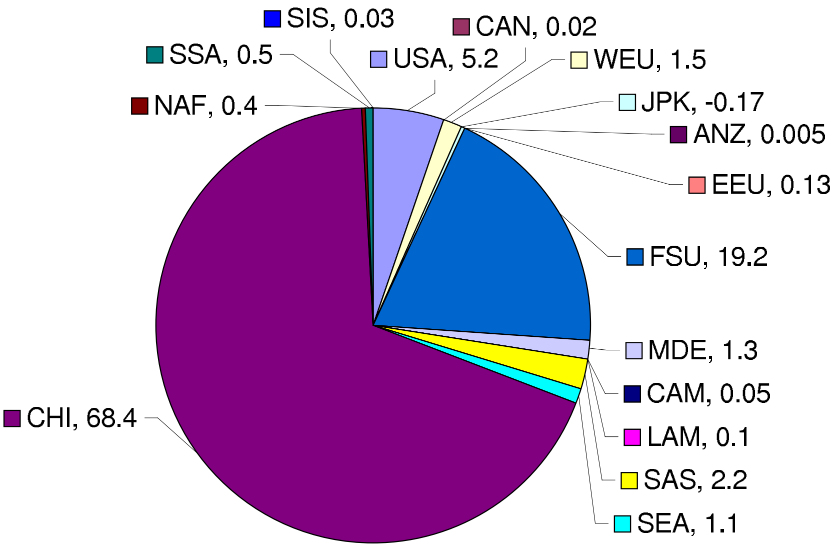

Figure 4.14: The share of abatement level for each region (in percentage) in atom structure, year 2025.

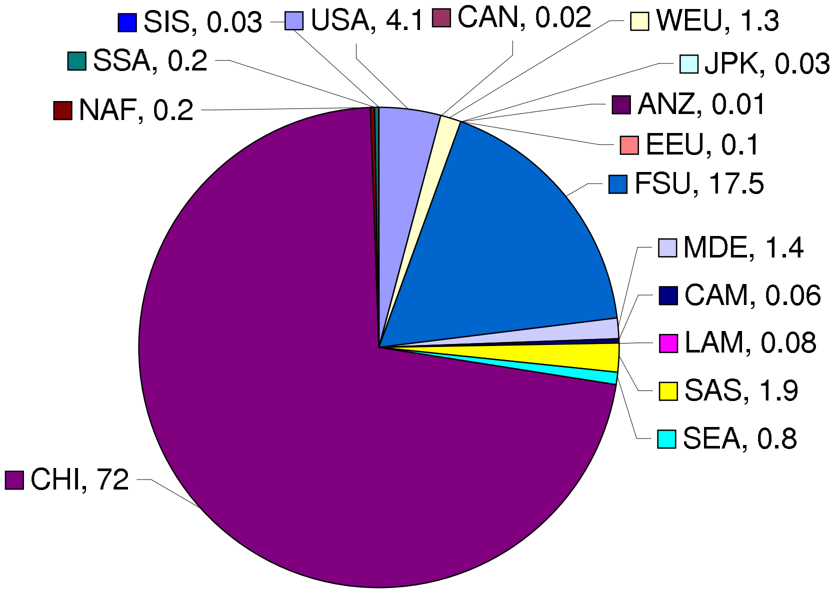

Figure 4.15: The share of abatement level for each region (in percentage) in atom structure, year 2045.

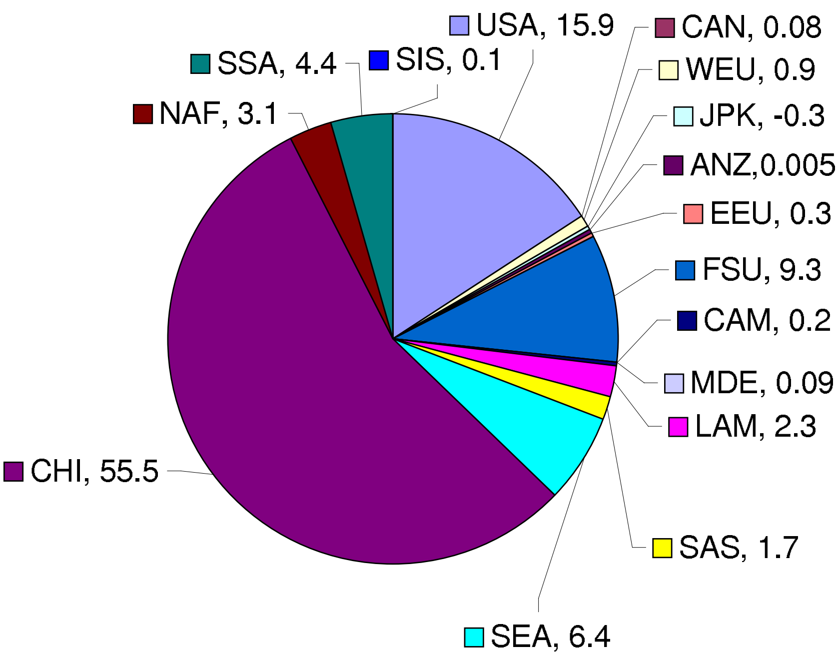

Figure 4.16: The share of abatement level for each region (in percentage) when two preferred farsighted stable coalition are formed, year 2005.

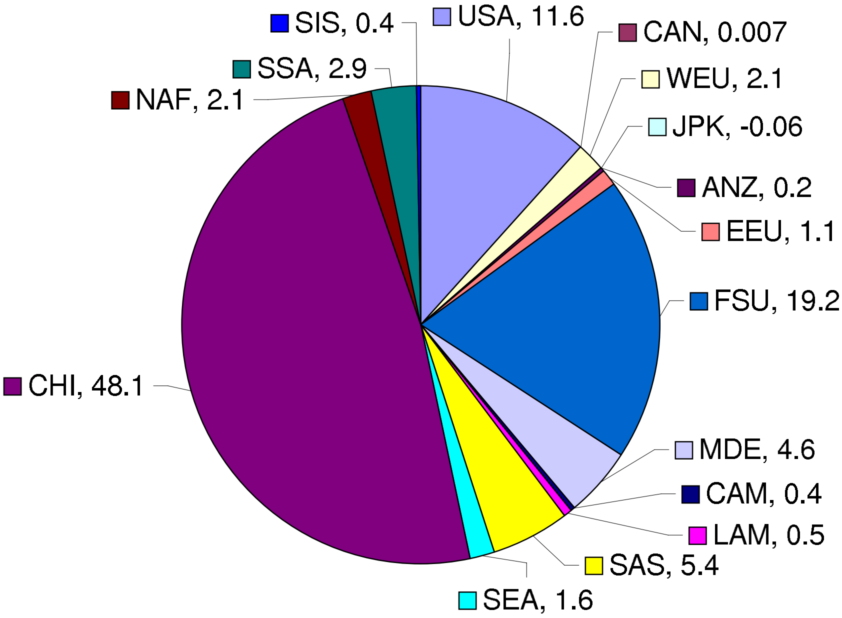

Figure 4.17: The share of abatement level for each region (in percentage) when two preferred farsighted stable coalition are formed, year 2025.

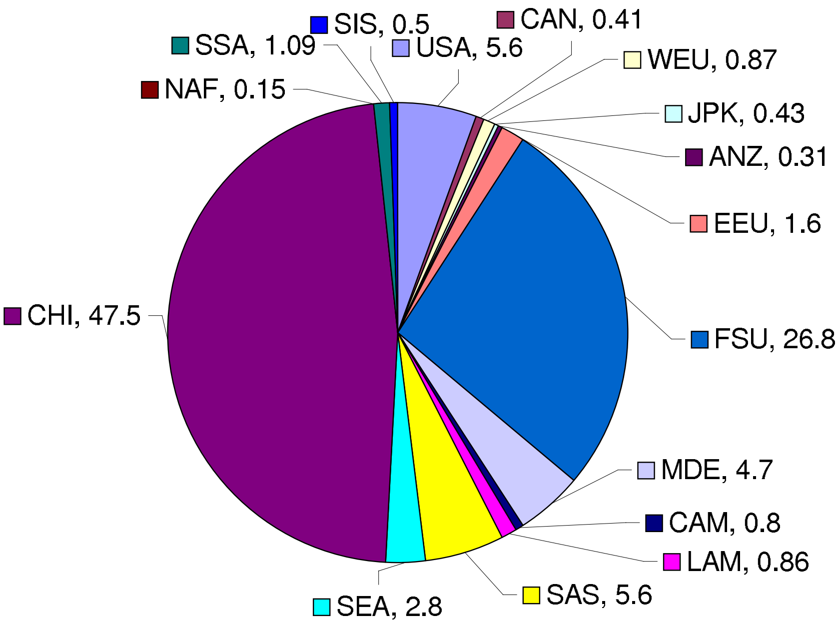

Figure 4.18: The share of abatement level for each region (in percentage) when two preferred farsighted stable coalition are formed, year 2045.

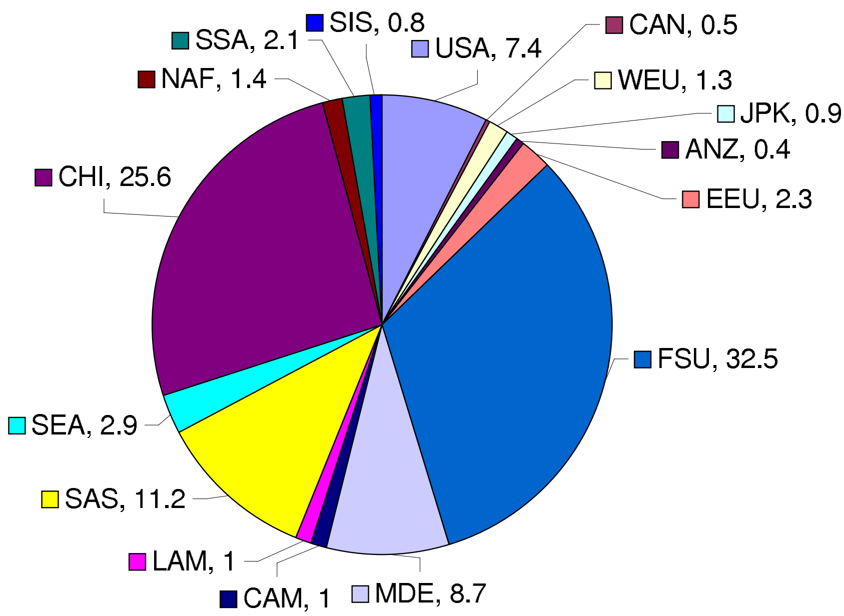

Figure 4.19: The share of abatement level for each region (in percentage) for grand coalition, year 2005.

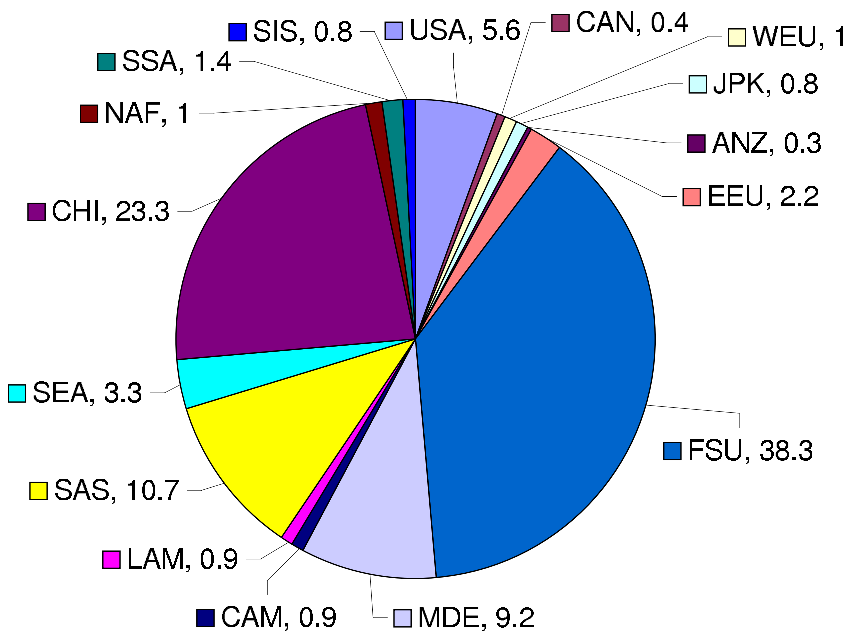

Figure 4.20: The share of abatement level for each region (in percentage) for grand coalition, year 2025.

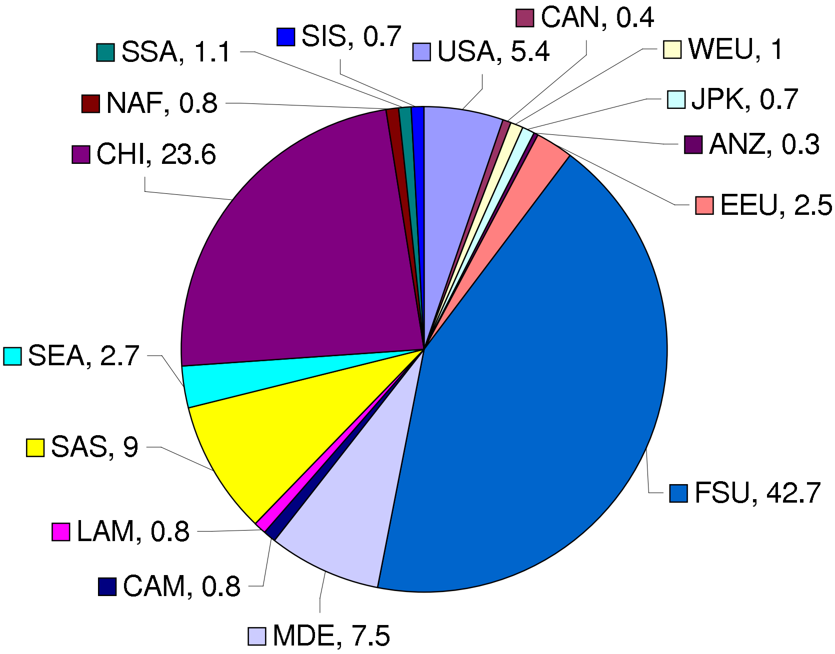

Figure 4.21: The share of abatement level for each region (in percentage) for grand coalition, year 2045.

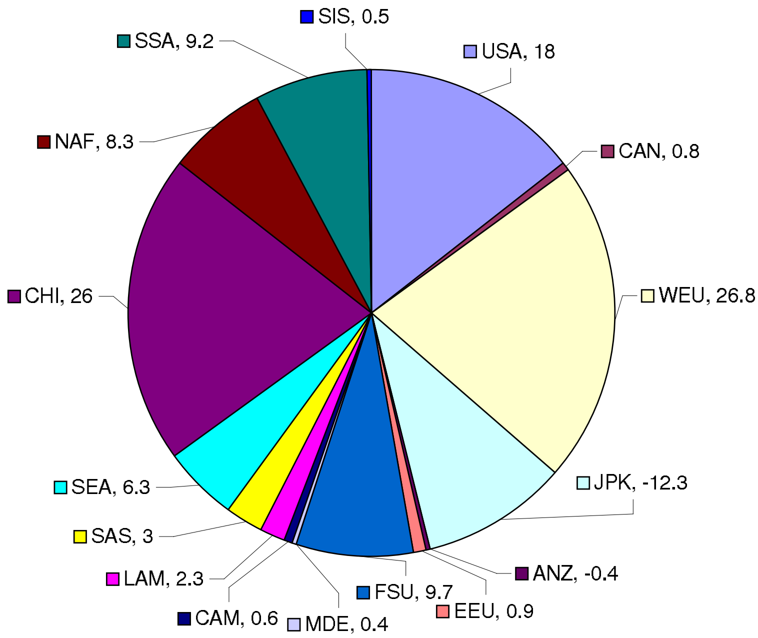

Figure 4.22: The profit share for each region (in percentage) in atom structure, year 2005.

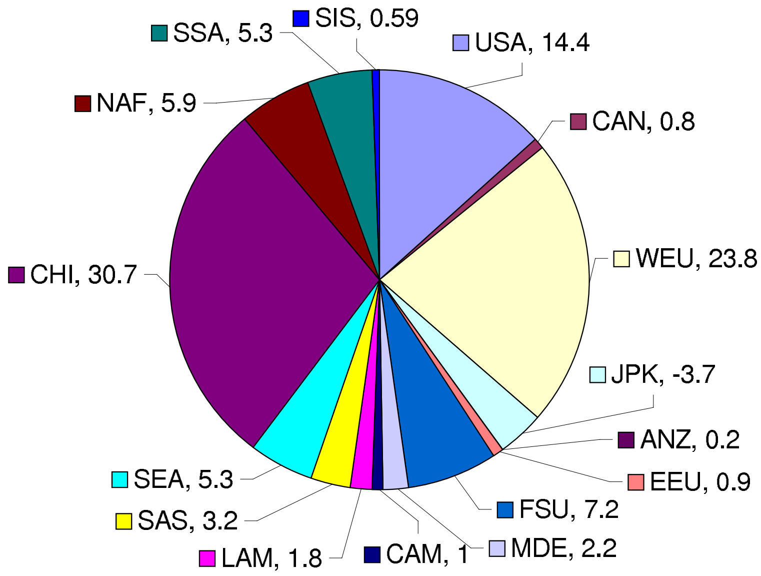

Figure 4.23: The profit share for each region (in percentage) in atom structure, year 2025.

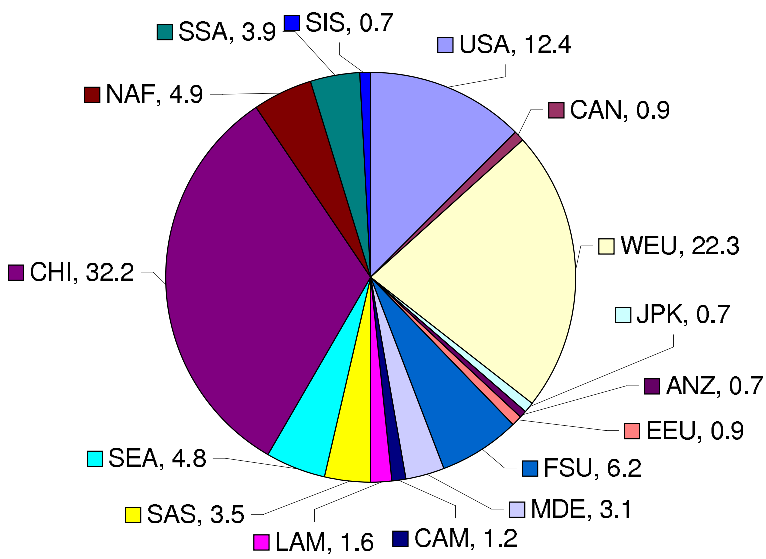

Figure 4.24: The profit share for each region (in percentage) in atom structure, year 2045.

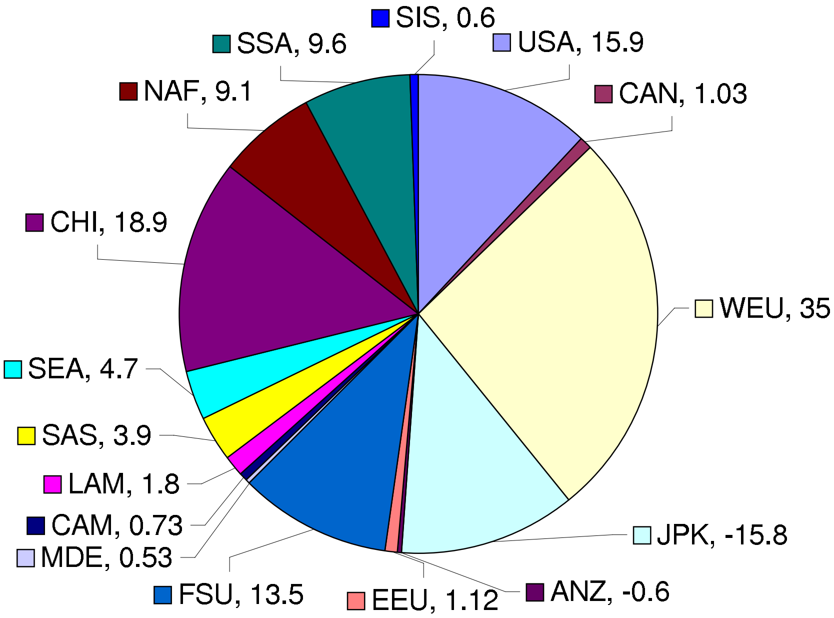

Figure 4.25: The profit share for each region (in percentage) when two preferred farsighted stable coalition are formed, year 2005.

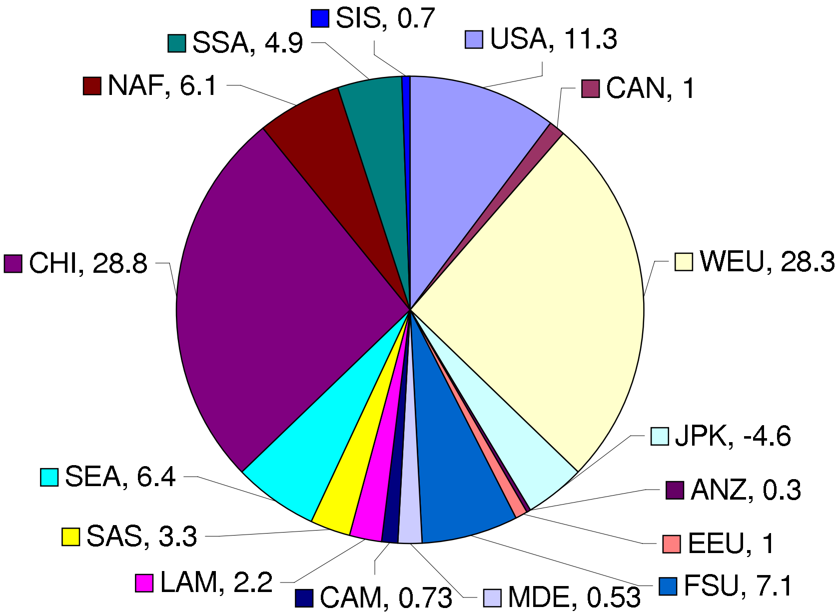

Figure 4.26: The profit share for each region (in percentage) when two preferred farsighted stable coalition are formed, year 2025.

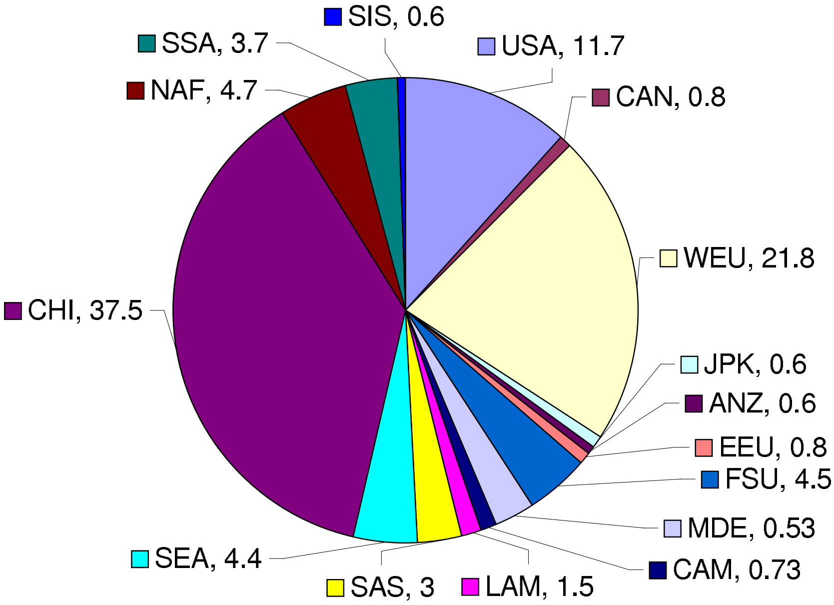

Figure 4.27: The profit share for each region (in percentage) when two preferred farsighted stable coalition are formed, year 2045.

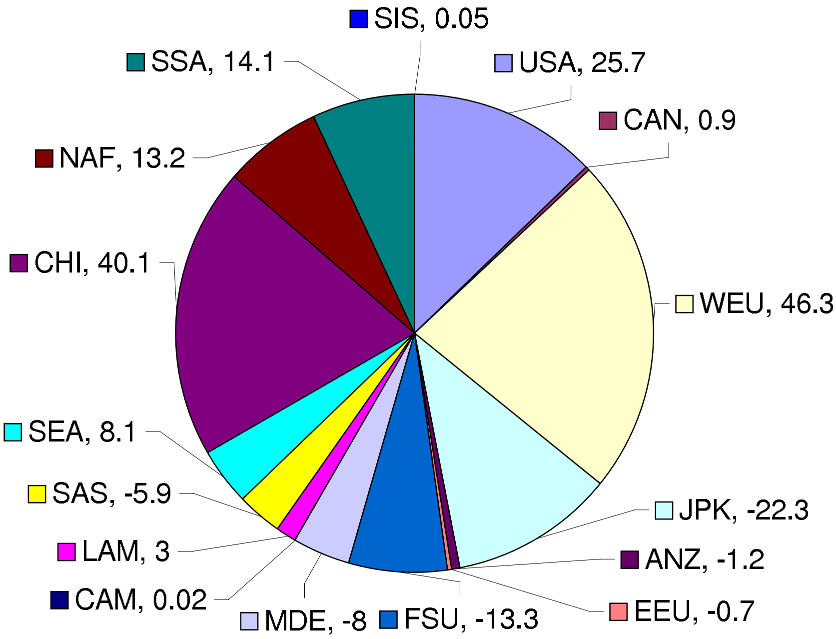

Figure 4.28: The profit share for each region (in percentage) in grand coalition, year 2005.

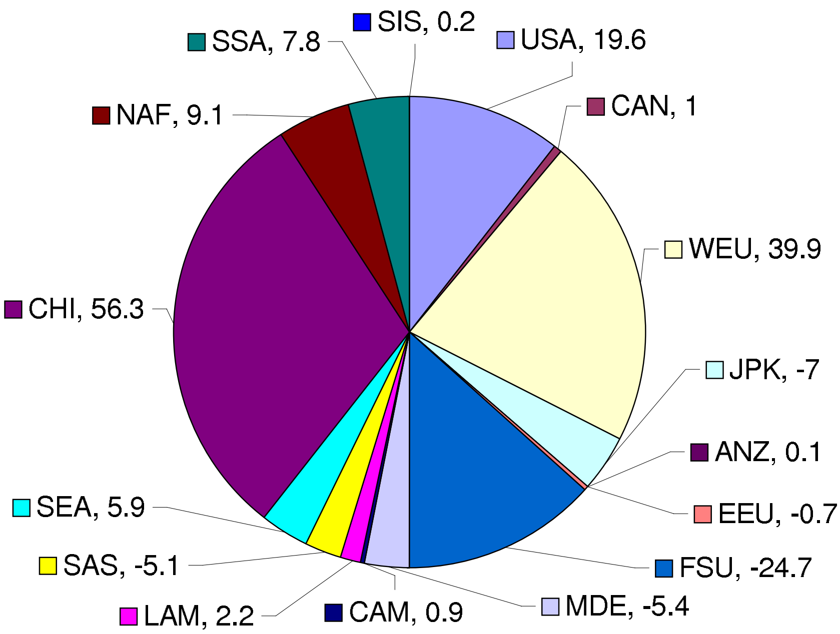

Figure 4.29: The profit share for each region (in percentage) in grand coalition, year 2025.

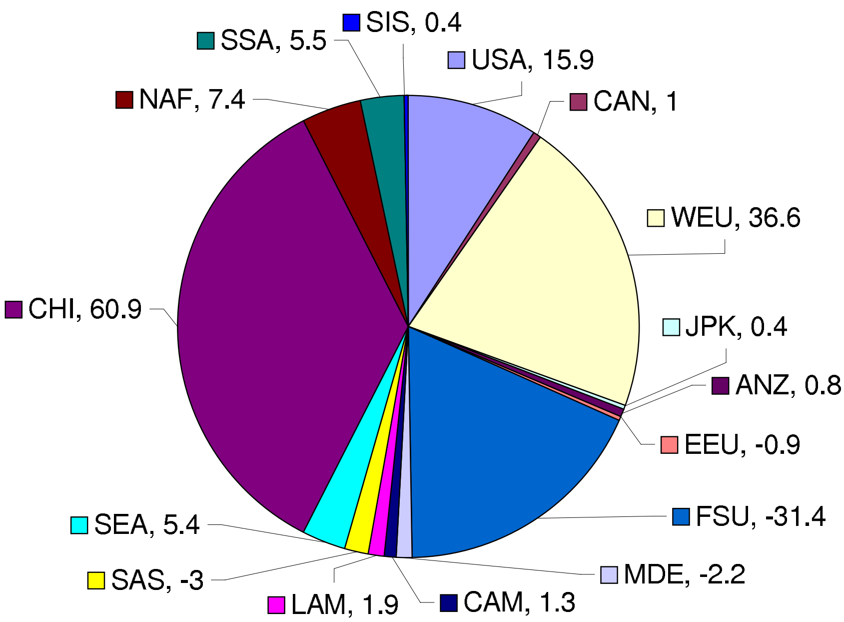

Figure 4.30: The profit share for each region (in percentage) in grand coalition, year 2045.

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Chapter 5

A Short Note on Joint Welfare Maximization Assumption

A short note on joint welfare maximization assumption

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Abstract

Non-cooperative game theoretical models of international environmental agreements (IEAs) use the assumption that coalition of signatories maximizes their joint welfare. The joint maximization assumption is compared with different welfare sharing schemes such as Shapley value, Nash bargaining solution and Consensus Value. The results show that the joint welfare maximization assumption is similar with Nash Bargaining solution.

Keywords: game theory, coalition formation, joint welfare maximization, Shapley value, Nash bargaining solution, Consensus Value, international environmental agreements.

JEL: C02, C72, H41

5.1 Introduction

The formation and implementation of International Environmental Agreements (IEA) is the topic of a broad economic literature. A significant part of the literature uses game theory as a tool to understand the formation mechanism of IEAs. There are two main directions of literature on IEAs (for a review of current literature see Finus 2003; Carraro/Siniscalco 1998; Ioannidis/Papandreou/Sartzetakis 2000; Carraro/Eyckmans/Finus 2005). The first direction utilizes the concepts of cooperative game theory in order to model the formation of IEAs. This is a rather optimistic view and it shows that an IEA signed by all countries is stable provided that utility is transferable and side payments are adequate (Chander/Tulkens 1995, 1997, 2006). The second direction uses the concepts of non-cooperative game theory to model the formation of IEAs (Barrett 1994, Osmani & Tol 2006, Rubio & Ulph 2006). At the first level, the link between the economic activity and the physical environment is established in order to generate the economical-ecological model. This link is established through a social welfare function. The social welfare function captures the difference between the profit from pollution and the environmental damage.
The Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model provides the social-welfare functions in our model.
Following this approach, countries play a two stage-game. In the first stage, each country decides to join the IEA, or to stay as non-member. In the second stage, every country decides on emissions. The main body of literature examining the formation of IEA within a two stage framework uses a certain set of assumptions. We mention below only the essential ones:

- Decisions are simultaneous in both stages.

- Countries are presented with single agreements.

- Stability of IEA's is based on the ideas developed for cartel stability (d'Aspremont et al. ((1983)) and requires so-called internal and external stability. Internal stability means that a country does not have an incentive to leave the coalition. External stability means that a country does not have an incentive to join the coalition. When defecting from coalition, a country assumes that all other countries remain in the coalition (this is a consequence of the employed stability concept of d'Aspremont et al that allows only singleton movements and myopia).

- Within the coalition, players players cooperatively and maximize their joint welfare, while the coalition and single countries compete in a non cooperative way.

Non-cooperative game theory draws a pessimistic picture of the prospect of successful cooperation between countries. It claims that a large coalition of signatories is hardly stable, and that the free-rider incentive is strong. The model explains the problems of international cooperation in the attendance of environmental spillovers, but cannot explain IEAs with high membership such as the Montreal Protocol. This calls for a modification of the standard assumptions. We mention in the following paragraphs some of the possible modifications.
Asheim et. al (2006), Carraro (2000) and Osmani & Tol (2006) allow more than one IEA to be formed. They reach the conclusion that two IEA's can perform better than one IEA in regional environmental problems.
Diamantoudi & Sartzetakis (2002), Eyckmans (2003) and Osmani & Tol (2007a,b) use the farsighted stability concept instead of D'Aspremont myopic stability. The farsighted stability is firstly introduced by Chwe (1994). The idea of farsightedness implies that one should check for multi-step stability by comparing the profits of a coalition member after a series of deviations has come to an end. Non-cooperative game theory predicts more optimistic results by employing farsighted stability.
The main contribution of the paper is the discussion on the assumption of *joint welfare maximization.* As the members of coalition *play cooperatively* we compare the joint welfare maximization with classical cooperative game theory value such as Shapley Value and Nash bargaining solution. We make use of farsightedly stable coalitions that comes form applying the *Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model* (see Osmani & Tol (2007a).
In section two, the FUND model is described. We continue with introducing our game-theoretic model, farsighted stability and coalitions that are going to be considered. In the next section, the different sharing schemes such as Shapley Value, Nash Bargaining and Consensus Value are presented. In fifth section section, our results are discussed. Section six concludes. In Appendix the results are introduced in eight different Tables.

5.2 FUND model

This paper uses version 2.8 of the Climate Framework for Uncertainty, Negotiation and Distribution (FUND). Version 2.8 of FUND corresponds to version 1.6, described and applied by Tol (1999a,b, 2001, 2002c), except for the impact module, which is described by Tol (2002a,b) and updated by Link and Tol (2004). A further difference is that the current version of the model distinguishes 16 instead of 9 regions. Finally, the model considers emission reduction of methane and nitrous oxide as well as carbon dioxide, as described by Tol (2006).
Essentially, FUND consists of a set of exogenous scenarios and endogenous perturbations. The model distinguishes 16 major regions of the world, viz. the United States of America (USA), Canada (CAN), Western Europe (WEU), Japan and South Korea (JPK), Australia and New Zealand (ANZ), Central and Eastern Europe (EEU), the former Soviet Union (FSU), the Middle East (MDE), Central America (CAM), South America (LAM), South Asia (SAS), Southeast Asia (SEA), China (CHI), North Africa (NAF), Sub-Saharan Africa (SSA), and Small Island States (SIS). The model runs from 1950 to 2300 in time steps of one year. The prime reason for starting in 1950 is to initialize the climate change impact module. In FUND, the impacts of climate change are assumed to depend on the impact of the previous year, this way reflecting the process of adjustment to climate change. Because the initial values to be used for the year 1950 cannot be approximated very well, both physical and monetized impacts of climate change tend to be misrepresented in the first few decades of the model runs. The period of 1950-1990

is used for the calibration of the model, which is based on the IMAGE 100-year database (Batjes, Goldewijk, 1994). The period 1990-2000 is based on observations (WRI, 2000). The climate scenarios for the period 2010-2100 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett et al., 1992). The 2000-2010 period is interpolated from the immediate past, and the period 2100-2300 extrapolated.

The scenarios are defined by the rates of population growth, economic growth, autonomous energy efficiency improvements as well as the rate of decarbonization of the energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from land use change, methane and nitrous oxide. The scenarios of economic and population growth are perturbed by the impact of climatic change. Population decreases with increasing climate change related deaths that result from changes in heat stress, cold stress,malaria, and tropical cyclones. Heat and cold stress are assumed to have an effect only on the elderly, non-reproductive population. In contrast, the other sources of mortality also affect the number of births. Heat stress only affects the urban population. The share of the urban population among the total population is based on the World Resources Databases (WRI, 2000). It is extrapolated based on the statistical relationship between urbanization and per-capita income, which are estimated from a cross-section of countries in 1995. Climate-induced migration between the regions of the world also causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The market impacts are dead-weight losses to the economy. Consumption and investment are reduced without changing the savings rate. As a result, climate change reduces long-term economic growth, although consumption is particularly affected in the short-term. Economic growth is also reduced by carbon dioxide abatement measures. The energy intensity of the economy and the carbon intensity of the energy supply autonomously decrease over time. This process can be accelerated by abatement policies, an option not considered in this paper.

The endogenous parts of FUND consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, the impact of carbon dioxide emission reductions on the economy and on emissions, and the impact of the damages to the economy and the population caused by climate change. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is represented by the five-box model of Maier-Reimer and Hasselmann (1987). Its parameters are taken from Hammitt et al. (1992). The model also contains sulphur emissions (Tol, forthcoming[a]).

The radiative forcing of carbon dioxide, methane, nitrous oxide and sulphur aerosols is determined based on Shine et al. (1990). The global mean temperature T is governed by a geometric build-up to its equilibrium (determined by the radiative forcing RF), with a half-life of 50 years. In the base case, the global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents. Regional temperature follows from multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs (Mendelsohn et al., 2000). The global mean sea level is also geometric, with its equilibrium level determined by the temperature and a half-life of 50 years. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario of Kattenberg et al. (1996).

The climate impact module, based on Tol (2002b,c) includes the following categories: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems. Climate change related damages can be attributed to either the rate of change (benchmarked at 0.04°C) or the level of change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (cf. Tol, 2002c). People can die prematurely due to temperature stress or vector-borne diseases, or they can migrate because of sea level rise. Like all impacts of climate change, these effects are monetized. The value of a statistical life is set to be 200 times the annual per capita income. The resulting value of a statistical life lies in the middle of the observed range of values in the literature (cf. Cline, 1992). The value of emigration is set to be 3 times the per capita income (Tol, 1995, 1996), the value of immigration is 40 per cent of the per capita income in the host region (Cline, 1992). Losses of dryland and wetlands due to sea level rise are modelled explicitly. The monetary value of a loss of one square kilometre of dryland was on average $4 million in OECD countries in 1990 (cf. Fankhauser, 1994). Dryland value is assumed to be proportional to GDP per square kilometre. Wetland losses are valued at $2 million per square kilometre on average in the OECD in 1990 (cf. Fankhauser, 1994). The wetland value is assumed to have logistic relation to per capita income. Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Other impact categories, such as agriculture, forestry, energy, water, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their 'natural' units (cf. Tol, 2002b). Impacts of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, which is determined by a variety of factors, including plant physiology and the behaviour of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative (cf. Tol, 2002c). The impacts of climate change on coastal zones, forestry, unmanaged ecosystems, water resources, diarrhoea malaria, dengue fever, and schistosomiasis are modelled as simple power functions. Impacts are either negative or positive, and they do not change sign (cf. Tol, 2002c). Vulnerability to climate change changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth), heat-related disorders (with urbanization), and ecosystems and health (with higher per capita incomes). Other systems are projected to become less vulnerable, such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) (cf. Tol, 2002c).
Note that we make use of data only for the year 2005. This is sufficient as static game theory is used but with a sophisticated stability concept.

Table 5.1: Our data from year 2005, α abatement cost parameter (unitless), β marginal damage costs of carbon dioxide emissions (in dollars per tonne of carbon) E carbon dioxide emissions (in billion metric tonnes of carbon) Y gross domestic product, in billion US dollar. Source: FUND

	α	β	E	Y
USA	0.01515466	2.19648488	1.647	10399
CAN	0.01516751	0.09315600	0.124	807
WEU	0.01568000	3.15719404	0.762	12575
JPK	0.01562780	-1.42089104	0.525	8528
ANZ	0.01510650	-0.05143806	0.079	446
EEU	0.01465218	0.10131831	0.177	407
FSU	0.01381774	1.27242378	0.811	629
MDE	0.01434659	0.04737632	0.424	614
CAM	0.01486421	0.06652486	0.115	388
LAM	0.01513700	0.26839935	0.223	1351
SAS	0.01436564	0.35566631	0.559	831
SEA	0.01484894	0.73159104	0.334	1094
CHI	0.01444354	4.35686225	1.431	2376
NAF	0.01459959	0.96627119	0.101	213
SSA	0.01459184	1.07375825	0.145	302
SIS	0.01434621	0.05549814	0.038	55

5.2.1 Welfare function of FUND model

For the analysis of coalition formation, we approximate the FUND model with a linear quadratic structure. Specifically, the abatement cost function is represented as:

$$C_i = \alpha_i R_i^2 Y_i \tag{5.1}$$

where C denotes cost, R relative emission reduction, and Y gross domestic product; i indexes regions; α is the cost parameter. The benefit function is approximated as:

$$B_i = \beta_i \sum_j^n R_j E_j \tag{5.2}$$

where B denotes benefit and E unabated emissions. Tables 5.1 gives the parameters of Equations (5.1) and (5.2) as estimated by or specified in FUND. Moreover the profit P is given as:

$$P_i = B_i - C_i = \beta_i \sum_j^n R_j E_j - \alpha_i R_i^2 Y_i \tag{5.3}$$

Non-cooperative optimal emission reduction is then:

$$dP_i/dR = \beta_i E_i - 2\alpha_i R_i Y_i = 0 \Rightarrow R_i = \beta_i E_i/(2\alpha_i Y_i) \tag{5.4}$$

If region i is in a coalition with region j, optimal emission reduction is:

$$dP_{i+j}/dR_i = 0 \Rightarrow E_i(\beta_i + \beta_j) - 2\alpha_i R_i Y_i = 0 \Rightarrow R_i = (\beta_i + \beta_j)E_i/(2\alpha_i Y_i) \tag{5.5}$$

The price for entering a coalition is therefore higher emission abatement at home. The return is that the coalition partners also raise their abatement efforts.
Note that our welfare functions are orthogonal, this indicates that the emissions change of a country do not affect the marginal benefits of other countries (independence assumption). In our game, countries outside the coalition benefit from the reduction in emissions achieved by the cooperating countries but they cannot affect the benefits derived by the members of the coalition. As our cost-benefit function are orthogonal our approach does not capture the effects of emissions leakage. But our cost benefit function are sufficiently realistic as they are approximation of complex model FUND and our procedure of dealing with farsighted stability is general and appropriate for non-orthogonal functions also.

5.3 Our model

There are 16 world regions (we name the set of all regions by N_{16}) in our game theoretic model of IEA's (or coalitions), which are shown in first column of Table 5.1. At the first level, the link between the economic activity and the physical environment is established in order to generate the economical-ecological model. This link is established through a social welfare function of FUND model, see 5.7. The social welfare function captures the difference between the profit from pollution and the environmental damage. Following this approach, countries play a two stage-game. In the first stage, each country decides to join the coalition $C \subseteq N_{16}$ and become a signatory (or coalition member) or stay singleton and non-signatory (*membership game*). These decisions lead to *coalition structure* S with c coalition-members (c denotes the cardinality of C) and 16-c non-members. *A coalition structure* simply fully describes how many coalitions (at the moment we assume that we have one coalition) are formed, how many members each coalition has and how many singleton players are. Given the simple coalition structure S is fully characterized by coalition C. In the second stage, every country decides on emissions (*strategic game*). Within the coalition, players play cooperatively (by maximizing their joint welfare) while the coalition and single countries compete in a non cooperative way (by maximizing their own welfare). Every coalition C is assigned a real number $\upsilon(C)$ (called characteristic function).

Definition 5.1 *By the* ***characteristic function*** *of our 16-player game (played by c and* $16-c$ *players, where c is cardinality of coalition C) we mean a real-valued function* $\upsilon(C) : C \to R$,
$\upsilon(C) = max(\sum_1^c \pi_i) \quad \forall i \in C, \quad C \subset N_{16}, \quad c \leq 16.$

Characteristic function is simple the total profit that coalition-member reach by maximizing their joint welfare. As π are strictly concave, their sum is strictly concave also, which simplifies the maximization problem. The game satisfies the superadditivity property:

Definition 5.2 *A game is superadditive if for any two coalitions,* $C_1 \subset N_{16}$ *and* $C_2 \subset N_{16}$:
$\upsilon(C_1 \cup C_2) > \upsilon(C_1) + \upsilon(C_2) \quad C_1 \cap C_2 = \emptyset.$

The *superadditivity property* means that if C_1 and C_2 are disjoint coalitions (here C_1 and C_2 can be single players too), it is clear that they should accomplish at least as much as by joining forces as by remaining separate. But the game *almost always (with some exceptions)* exhibits *positive spillovers:*

Definition 5.3 *A game exhibits positive spillover property if and only if for any two coalitions* $C_1 \subset N_{16}$ *and* $C_2 \subset N_{16}$ *such as* $C_1 \nsubseteq C_2$ *and* $C_2 \nsubseteq C_1$ *we have:*
$\forall k \notin C_1 \cup C_2 \quad \upsilon_k(C_1 \cup C_2) > \upsilon_k(C_1) \wedge \upsilon_k(C_1 \cup C_2) > \upsilon_k(C_2)$

It indicates that there is an external gain (C_1 and C_2 can be single players too) or a positive spillover from cooperation, making free-riding (i.e., not joining $C_1 \cup C_2$) attractive. It just implies that every player $k \notin C_1 \cup C_2$ has higher profit when two coalitions C_1 and C_2 cooperate compared to the situation where two coalitions stay separated. It indicates that from a non-signatory's point of view (player k here), the most favorable situation is the one in which all other countries take part in the coalition (except k). As we have already mentioned the positive spillover property is almost always satisfied with the exception of some coalitions that contain as members Japan & South Korea or Australia & New Zealand which have negative marginal benefits (negative β's) from pollution abatement.
As our game is formally defined, we concentrate the attention to farsighted stability. In our model framework, the farsighted stability is mainly based in two arguments. The first one is the *coalition change process* (sometimes we will call it *coalition inducement*[1]) which includes all possible was that a coalition can change. Basically coalition change process solves the question: Can a part of members of our coalition (or all) improve their welfare (by help of non-member coalition or not) by forming a new coalition. The players are farsighted in the first sense that they check all possible ways for forming a new coalition in order to improve their welfare. The second arguments is a behavioral assumption for our farsighted players (or regions) in order to deter free-riding. Suppose that there is no way to improve the welfare for a coalition, but a country can still free-ride and improve his welfare alone! We assume that our players are farsighted in another sense namely they refuse to free-ride because they take into account that the other members of coalition can act similarly, which will finally result in welfare decrease for everyone.

5.3.1 Farsightedly stable coalitions

Below a short introduction of farsighted stability is introduced, and then farsighted coalitions ,which we are going to consider, are presented.
As we will consider only profitable coalition. The situation in which each country maximizes its own profit is referred to as *the atom structure*; it is a standard Nash equilibrium; the maximum coalition size is unity. A coalition that performs better than atom-structure is *a profitable coalition.* We limit our attention to coalitions, which are profitable and this is sufficient to find all farsightedly stable coalitions[2].
We concentrate in *the different ways that a coalition can change.* There are four ways[3] of a *coalition change* (or *coalition inducement*); the coalition gets bigger; gets smaller; some coalition-member leave coalition and some other join it; fourth way is a special one, namely *the free-riding*, one country or more leave the coalition and increase their welfare.
If a coalition get bigger, it follows that the original members of coalitions see an increase in profits and the new members see an increase too; we say that an external inducement is possible. This can be easily checked by a combinatorial algorithm.

Definition 5.4 *If no external inducement is possible than the coalition is external farsightedly stable (EFS).*

If a coalition gets smaller, its remaining members see an increase in profits; we say that an internal inducement is possible.

Definition 5.5 *If no internal inducement is possible than the coalition is internal farsightedly stable (IFS).*

The third way of coalition inducement is if a number of old coalition members leave and a number of new members join the coalition. The new coalition may be larger or smaller than the original one. One

[1] In our previous paper Osmani & Tol (2007a) in stead of concept *coalition change process* we use only the notation of *inducement process* by introducing a strict definition of it.
[2] See Observation 3.1 in Osmani & Tol (2007a).
[3] We also introduce five ways of inducement process in Osmani & Tol (2007a), and here only four, as we present a short introduction only.

needs to check if countries in a final coalition increase their profits by forming a new coalition. We call it *sub-coalition inducement.*

Definition 5.6 *If no sub-coalition inducement is possible than the coalition is sub-coalition farsightedly stable (SFS).*

It needs more combinatorial work to check if a sub-coalition inducement is possible.
As we noted one special coalitional change is caused by free-riding. In our model, free-riding is deterred based on motivation that originates from experimental game theory (Fehr & Gächter (2000), Ostrom (2000))[4], which predicts that if a player free-rides, as the rest of players get this information, a part of them (not all) is going to free-ride also. This results in worsening of the welfare for every player. We assume that our players (countries in our approach) possess the knowledge that if free-riding appears, it will be spread out and other players countries will start to free-ride. This assumption deters free-riding and fits well to farsighted behavior as takes into account the counter reaction of other countries. As free-riding is prevented based on behavioral assumption, which implies that there is no free-riding for any coalitions then inducement caused by free-riding can not be included in definition of farsighted stability. Now we are able to present the definition of farsighted stability:

Definition 5.7 *If no internal, external and sub-coalition improvement is possible than the coalition is farsightedly stable.*

Testing a coalition for farsighted stability means comparing the profit of his country members with *the profit of country members of all possible coalitions (that can be induced or not) and finding the coalitions that can be induced.* The farsightedly stable coalition that will be discussed are:

$(USA, LAM, SEA, CHI, NAF, SSA)$
$(CAN, EEU, CAM, SAS, SIS)$

Further more we are going to discuss two sub-coalitions of above coalitions:

$(USA, SEA, CHI, NAF, SSA)$
(CAN, EEU, CAM, SAS)

For a more detailed description how the farsightedly stable coalitions are found please see Osmani & Tol (2007a).

5.4 Different sharing schemes

The joint welfare maximization is compared with Shapley Value, Nash Bargaining solution and Consensus Value. In the following subsection we will describe them shortly.

5.4.1 Shapley Value

Suppose we form a coalition C by entering the players into this coalition one at a time; $v(C)$ is the *characteristic function* of coalition C, see definition 5.1; $|C|$ is cardinality of coalition C, and n is total number of players. As each player enters the coalition, he receives the amount by which his entry increases the value of the coalition he enters. The Shapley value (Shapley 1953) is just the average payoff to the players if the players are entered in completely random order.

Definition 5.8 *The Shapley value is given by,* $\phi = (\phi_1, ..., \phi_n)$ *where for* $i = 1, ..., n$*:*

$$\phi_i(v) = \sum_{C \subset N, i \subset C} \frac{(|C|-1)!(n-|C|)!}{n!}(v(C) - v(C - \{i\})) \tag{5.6}$$

The interpretation of this formula is as follows. Suppose we choose a random order of the players with all n! orders (permutations) of the players equally likely. Then we enter the players according to this order. If, when player i enters, he forms coalition C (that is, if he finds $C - \{i\}$ there already), he receives

[4]The mentioned papers consider behavior of the people not of countries as we would like. But we consider the assumption (on spreading of free-riding behavior) relevant for our framework as it go well with the spirit of farsighted behavior and takes into account the counter reaction of other players.

the amount $(v(C) - v(C - \{i\}))$. The probability that when i enters he will find coalition $C - \{i\}$ there already is $\frac{(|C|-1)!(n-|C|)!}{n!}$. The denominator is the total number of permutations of the n players. The numerator is number of these permutations in which the $|C|-1$ members of $C - \{i\}$ come first ($(|C|-1)!$ ways), then player i, and then the remaining $n - |C|$ players ($(n - |C|)!$ ways). So this formula shows that $\phi_i(v)$ is just the average amount player i contributes to the coalitions if the players sequentially form those coalitions in a random order (and in all possible ways).

5.4.2 Nash Bargaining solution

The axiomatic theory of bargaining originated in a fundamental paper by Nash (1950), we simply adapt it to our problem. If a part (or all) of countries (we suppose that we have six countries without loss of generality) agree to form a coalition and behave cooperatively and the rest of countries optimize their own welfare function. We concentrate to 6 countries that form the coalition. The scenario is that 6 world regions have access to any of the alternatives in some set $\Re^6$, called the feasible utility set. Their preferences over the alternatives in the utility set are given by welfare function P:

$$P_i = B_i - C_i = \beta_i \sum_j^n R_j E_j - \alpha_i R_i^2 Y_i \tag{5.7}$$

where C denotes cost, R relative emission reduction, and Y gross domestic product; i indexes regions; α is the cost parameter; B denotes benefit and E unabated emissions.
If no coalition is formed, they end up at a pre-specified alternative in the feasible set called the disagreement point, which is denoted by vector d. In our model d is *profit vector of atom structure* with 6 elements where every country optimize his own profits. More formally, a bargaining problem is defined by the tuple $(\Re^6; d)$ where the utility set $(\Re^6)$ has to be (and is) a non-empty, convex, and compact subset. We further assume that there exists an $p \in \Re^6$, such that $p \gg d$. In our case, Nash bargaining solution, denoted $f_N(\Re^6; d)$ is given by

$f_N(\Re^6; d) = \arg\max \prod_{i=1...6}(P_i - d_i) \quad where \quad P_i = B_i - C_i = \beta_i \sum_j^n R_j E_j - \alpha_i R_i^2 Y_i$

This means simply we need to find the abatement level R of 6 coalition members that maximize f_N (as P_i is function of R). Note than the abatement level R of ten remaining countries are known as they simply maximize their own welfare function (we need them in order to calculate the benefit function $B_i = \beta_i \sum_j^n R_j E_j$).

5.4.3 Consensus Value

Let us consider an arbitrary 2-person cooperative TU game with player set $N = \{1, 2\}$ and characteristic function v determined by the values: $v(\{1\}), v(\{2\})$ and $v(\{1, 2\})$. A reasonable solution is that player 1 gets:

$v(\{1\}) + [v(\{1, 2\}) - v(\{1\}) - v(\{2\})]/2$

and player 2 gets:

$v(\{2\}) + [v(\{1, 2\}) - v(\{2\}) - v(\{1\})]/2$

That is, the (net) surplus generated by the cooperation between player 1 and 2, $v(\{1, 2\}) - v(\{2\}) - v(\{1\})$, is equally shared between the two players. This solution is called the standard solution for 2-person cooperative games. Ju, Y., Borm, P., Ruys, P. (2004) provide a generalization of the standard solution for 2-person games into n-person cases. Consider a n-person game (N, v) while the grand coalition $C_n = \{1, 2, .., n\}$ is formed than the player $(n + 1)$ (let call the new player just player (n+1)) joins the coalition and the coalition $C_{n+1} = \{1, 2, .., n, n+1\}$ is formed. The generalization of player $(n+1)$ share is:

$$\underbrace{v(\{n+1\})}_{v\ of\ the\ single\ player\ (n+1)} + \underbrace{[v(\{1, ..., n+1\}) - v(\{n+1\}) - v(\{1, .., n\})]}_{the\ surplus\ from\ cooperation\ of\ C_n\ and\ player\ (n+1)} \cdot 1/2$$

The interpretation of above formula is as follows. We can see the above situation as 2-person game. The coalition $C_n = \{1, 2, .., n\}$ is considered as one player and the next player is the new player $(n + 1)$

that joins the coalition. The (net) surplus generated by the cooperation between coalition C_n and the new player is $v(\{1,...,n+1\}) - v(\{n+1\}) - v(\{1,..,n\})$. The equation above says that the new player take the amount he gets alone $v(\{n+1\})$ plus the half of the surplus.

$$\underbrace{v(\{i \mid i \in C_n\})}_{v\ of\ a\ member\ of\ C_n} + \underbrace{[v(\{1,...,n+1\}) - v(\{n+1\}) - v(\{1,..,n\})]}_{the\ surplus\ from\ cooperation\ of\ C_n\ and\ player\ (n+1)} \cdot 1/2 \cdot 1/n$$

Each of n-players that was already in coalition C_n gets his payoff as member of coalition C_n plus half of the surplus divided by n.

5.5 Results

Before presenting results, we define:

$P_{joint}, P_{shap}, P_{nash}, P_{cons}$: the sharing profit according to joint welfare maximization, Shapley Value, Nash Bargaining solution and Consensus Value.

$\frac{(P_{joint}-P_{shap})}{P_{joint}} \cdot 100$: relative difference in percentage between joint welfare maximization and Shapley value.

$\frac{(P_{joint}-P_{nash})}{P_{joint}} \cdot 100$: relative difference in percentage between joint welfare maximization and Nash Bargaining Solution.

$\frac{(P_{joint}-P_{cons})}{P_{joint}} \cdot 100$: relative difference in percentage between joint welfare maximization and Consensus Value.

Our numerical computations are programmed in Matlab[5] programming language, and results are introduced in Appendix. Table (5.2) presents the results for the first coalition $(USA, LAM, SEA, CHI, NAF, SSA)$, Table (5.3) for the second coalition $(CAN, EEU, CAM, SAS, SIS)$, Table (5.4) for the third coalition $(USA, SEA, CHI, NAF, SSA)$ and Table (5.5) for the forth coalition (CAN, EEU, CAM, SAS). The Tables are similar, in the first column are coalition members, and in the second, third and fourth column the relative differences of joint welfare maximization compared to Shapley Value, Nash Bargaining Solution and Consensus Value.
The results show that joint welfare maximization is very similar to Nash Bargaining solution. Their relative differences are almost always less than 1% for four coalitions (in only one case more than 1%). The Shapley Value and Consensus Value differ significantly to joint welfare maximization for the first and third coalition, but they are similar for the second and fourth coalition.
In order to have a more complete picture of results, the absolute value of joint welfare maximization, Shapley Value, Nash Bargaining Solution and Consensus Value for every coalition[6] are provided in Table (5.6), Table (5.7), Table (5.8) and Table (5.9). The Tables are identical, in the first column are coalition members, and in the second, third, fourth and fifth column are values of joint welfare maximization, Shapley Value, Nash Bargaining Solution and Consensus Value. The last row presents the sum of all coalitions members value for every welfare sharing scheme used. It is clear that the sum has to be equal for every welfare sharing scheme used (for the same coalition), but due to round errors they are only approximately the same. The errors are less than 0.01 for the first coalition $(USA, LAM, SEA, CHI, NAF, SSA)$, and less than 0.001 for all three other coalitions.

. . .

One way to see the numerical comparisons, is that Shapley and Consensus Value take into account *the possible ways of coalition formation.* The Shapley Value considers all the ways of coalition formation while the Consensus Value assumes a specific way of coalition formation. On the opposite the joint welfare maximization and Nash Bargaining Solution are ways of maximizing the total profit of coalition *without considering how the coalition is formed.*

[5]Programs can be provided to the reader on request.
[6]The absolute values ca be also used to check the validity of conclusions.

5.6 Conclusions

The literature in international environmental agreements supposes that countries within a coalition maximize their joint welfare while the single countries play non-cooperatively against the coalition and against each-other. We investigate if joint welfare maximization shares the welfare level fairly among coalition members. The joint welfare maximization is compared to classical cooperative game value like Shapley Value, Nash bargaining solution and Consensus Value for four different coalitions. The Nash bargaining solution gives similar solution compared to joint welfare maximization. The Shapley Value and Consensus Value differ significantly compared to joint welfare maximization. One can consider the joint welfare maximization as reasonable assumption as it is similar also with another well-known scheme such as Nash Bargaining solution. Further work is needed in considering more coalitions and approaches that are more general.

5.7 Appendix

Table 5.2: The relative differences (in percentage) between the joint welfare maximization and three other different sharing schemes, respectively Shapley value, Nash bargaining solution and Consensus Value for coalition ($USA, LAM, SEA, CHI, NAF, SSA$).

Coalition members	Shapley Value	Nash Bargaining	Consensus Value
USA	3.7 %	0.022 %	9.4 %
LAM	-27.2 %	-0.69 %	-49.9 %
SEA	-26.0 %	-0.18 %	-51.7 %
CHI	-15.4 %	0.27 %	-0.82 %
NAF	24.1 %	-0.78 %	13.3 %
SSA	18.6 %	0.43 %	8.0 %

Table 5.3: The relative differences (in percentage) between the joint welfare maximization and three other different sharing schemes, respectively Shapley value, Nash bargaining solution and Consensus Value for coalition (CAN, EEU, CAM, SAS, SIS).

Coalition members	Shapley Value	Nash Bargaining	Consensus Value
CAN	1.25 %	0.27 %	1.25 %
EEU	-0.92 %	0.46 %	-0.46 %
CAM	-0.15 %	0.55 %	-0.15 %
SAS	-0.13 %	0.0013 %	0.0013 %
SIS	0.04 %	-0.79 %	-0.79 %

Table 5.4: The relative differences (in percentage) between the joint welfare maximization and three other different sharing schemes, respectively Shapley value, Nash bargaining solution and Consensus Value for coalition $(USA, SEA, CHI, NAF, SSA)$.

Coalition members	Shapley Value	Nash Bargaining	Consensus Value
USA	2.47 %	0.49 %	7.29 %
SEA	-27.27 %	-3.26 %	-51.82 %
CHI	-15.07 %	0.28 %	-2.62 %
NAF	22.71 %	0.1 %	12.42 %
SSA	17.2 %	0.12 %	6.76 %

Table 5.5: The relative differences (in percentage) between the joint welfare maximization and three other different sharing schemes, respectively Shapley value, Nash bargaining solution and Consensus Value for coalition (CAN, EEU, CAM, SAS).

Coalition members	Shapley Value	Nash Bargaining	Consensus Value
CAN	0.99 %	0 %	0.49 %
EEU	-0.92 %	-0.46 %	-0.92 %
CAM	0 %	-0.7 %	-0.7 %
SAS	0 %	0.13 %	0 %

Table 5.6: The absolute value of Joint Welfare Maximization and three other different sharing schemes, respectively Shapley value, Nash bargaining solution and Consensus Value for coalition $(USA, LAM, SEA, CHI, NAF, SSA)$.

Coalition members	Joint Welfare Max.	Shapley Value	Nash Bargaining	Consensus Value
USA	0.7218	0.6953	0.7216	0.6539
LAM	0.0806	0.1026	0.0812	0.1209
SEA	0.2143	0.27	0.2147	0.3251
CHI	0.8443	0.9747	0.842	0.8512
NAF	0.4163	0.316	0.4195	0.3609
SSA	0.4367	0.3554	0.4348	0.4019
—	2.714	2.714	2.7138	2.7139

Table 5.7: The absolute value of Joint Welfare Maximization and three other different sharing schemes, respectively Shapley value, Nash bargaining solution and Consensus Value for coalition $(CAN, EEU, CAM, SAS, SIS)$.

Coalition members	Joint Welfare Max.	Shapley Value	Nash Bargaining	Consensus Value
CAN	0.0204	0.0201	0.0203	0.0201
EEU	0.0217	0.0219	0.0216	0.0218
CAM	0.0144	0.0144	0.0143	0.0144
SAS	0.0753	0.0754	0.0753	0.0753
SIS	0.012	0.012	0.0121	0.0121
—	0.1438	0.1438	0.1436	0.1437

Table 5.8: The absolute value of Joint Welfare Maximization and three other different sharing schemes, respectively Shapley value, Nash bargaining solution and Consensus Value for coalition $(USA, SEA, CHI, NAF, SSA)$.

Coalition members	Joint Welfare Max.	Shapley Value	Nash Bargaining	Consensus Value
USA	0.6916	0.6745	0.6882	0.6412
SEA	0.2057	0.2618	0.2124	0.8384
CHI	0.817	0.9401	0.8147	0.3123
NAF	0.3976	0.3073	0.3972	0.3891
SSA	0.4173	0.3455	0.4168	0.3482
—	2.5292	2.5292	2.5293	2.5292

Table 5.9: The absolute value of Joint Welfare Maximization and three other different sharing schemes, respectively Shapley value, Nash bargaining solution and Consensus Value for coalition (CAN, EEU, CAM, SAS).

Coalition members	Joint Welfare Max.	Shapley Value	Nash Bargaining	Consensus Value
CAN	0.0202	0.02	0.0202	0.0201
EEU	0.0216	0.0218	0.0217	0.0218
CAM	0.0143	0.0143	0.0144	0.0144
SAS	0.0752	0.0752	0.0751	0.0752
—	0.1313	0.1313	0.1314	0.1315

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Chapter 6

Burden Sharing Emissions and Climate Change: A Theoretic Welfare Approach

Burden Sharing Emissions and Climate Change: A Theoretic Welfare Approach

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Abstract

The approximated cost-benefit function of pollution abatement from two integrated assessment models are employed in constructing of social welfare functions (SWF). Following a normative approach and evaluating equally the environmental goods in rich and poor countries, furthermore using distributional weights, a relation between elasticity of marginal utility e and inequality aversion parameter γ is established. By maximizing the global social welfare, the optimal pollution abatement level are found. The relation between the income elasticity of marginal utility e and the inequality aversion parameter γ allow to narrow the variation of e for a particular value of γ. As a consequence, smaller variation for optimal abatement levels are obtained, which allows to inspect if the Kyoto abatement objectives respect the requirement of evaluating equally the environmental goods in rich and poor countries.

Keywords: welfare theory, distributional weights, integrated assessment modeling.

JEL: D61, D62, D63

6.1 Introduction

Environmental equity is a sensible concept in global warming debates. It addresses the distributional issue which is the cumbersome point of benefit-cost analysis. As per capita income is lower in poor countries, then willingness-to-pay based estimates of damages in poor countries are lower than in the developed countries even though the impact is identical in human, physical or ecological terms. One way of managing this would be to use a normative approach by introducing weight factors based on the different marginal value of money in the different regions of the world. This would give higher weight to costs in the poor countries. Environmental equity can be understood as assuming a new decision criterium that requires that the value of lost lives (also any environmental goods) in rich and poor countries has to be weighted differently. The normative approach is not realistic as it does not respect the WTP estimates which are the base of economic valuation. However, I would like to experiment in order to test the Kyoto emissions reduction targets requiring that the value of life is identical in poor and rich countries.

There are different views in favor and against of using weight factors. I do not plan to review this discussion. I simply assume that weight factors are considered appropriate from a normative point of view, and then examine if the Kyoto emissions reduction targets are consistent with the requirement of valuing the life in poor and developed countries by weighting them differently.

Following Ray (1984) and Stenman (2000) I obtain the equity weights by totally differentiating the social welfare function. The social welfare function depends on three parameters, which are the incomes per capita, the elasticity of marginal utility e and the inequality aversion parameter γ. The incomes per capita depend on GDP, population and costs and benefits from pollution abatement which are obtained from two different integrated assessment models namely the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model developed by Richard Tol, and the MITs Emissions Prediction and Policy Analysis (EPPA) model developed at MIT. The essential point of the paper is the development of a relation between e and γ by equalizing the value of life in poor and rich regions following Fankhauser et al. (1997) and Stenman (2000), but allowing for larger range of parameters values that relates e and γ. As e and γ take their values in specific intervals, there is a significant advantage to have a relation between them, as it is possible to restrict the intervals for e and γ when the world regions are approximated in only two types, namely poor and rich. That is, when the world social welfare for different e and γ is maximized (a global welfare optimization problem is built) and pollution abatements levels are found, one focuses on smaller intervals for e and γ which are going to give smaller variation for abatement levels. Finally it is possible to test if the abatement targets of Kyoto protocol respect the condition that the value of life is identical in poor and rich countries when equity weights are used. The costs and benefits from pollution abatements are calculated for the year 2010, which is considered as the representative year of the first commitment period of Kyoto protocol that includes the years 2008 through 2012.

The optimization global welfare models are similar to Eyckmans et al. (2002), Rose et al. (1998) and Rose & Stevens (1993). Eyckmans et al. (2002) maximize a social welfare function (only for EU) with only one parameter, namely e, which is less general that our social welfare function with two parameters, namely e and γ. Rose et al. (1998) minimize cost of pollution abatement (or maximize benefits in Rose & Stevens (1993)) and use different international equity criteria, while in this paper a social welfare function is maximized when value of life is equal to rich and poor countries.

The paper is structured as follows. Section two reviews the utility and welfare functions and derive equity weights. The section works with different types of welfare functions, including the utilitarian ($\gamma = 0$), Bernoulli-Nash ($\gamma = 1$), and a special welfare function for $\gamma = 2$[1]. Section three assumes that the value of life in poor and developed countries is the same by weighting them differently in order to derive a relation between the elasticity of marginal utility$e$ and the inequality aversion parameter γ. Section four presents the optimization global welfare models without permit systems and with permit systems for two different integrated assessment models, FUND and EPPA. The sixth section presents the results. Section seven provide the conclusions. The appendix one contains different tables which present the relation between e and γ, main parameters of FUND and EPPA models, and Figures that illustrate the optimal abatement levels of poor and rich regions. In the appendix two the results of EPPA and FUND model without permits system are compared.

6.2 Utility, Welfare Function and Equity Weights

It is common to use a conventional iso-elastic utility function that depends solely on consumption:

$$u = \begin{cases} \dfrac{Y^{(1-e)}}{1-e} + u_0 \ , & e \neq 1 \\ ln(Y) + u_0 \ , & e = 1 \end{cases} \tag{6.1}$$

where $e = -[du'/dY]Y/u' = -Yu''/u'$ is the income elasticity of marginal utility which shows that e is a measure of the curvature of u(Y).

The class of welfare functions for which inequality parameter γ is constant is given by the Bergson-Samuelson form:

$$W = \begin{cases} \sum_{i=1:n} \dfrac{u_i^{(1-\gamma)}}{1-\gamma} \ , & \gamma \neq 1 \\ \sum_{i=1:n} ln(u_i) \ , & \gamma = 1 \end{cases} \tag{6.2}$$

where γ is the parameter of inequality aversion. The smaller is γ, the smaller is the worry about equality. For $\gamma = 0$, equation implies the classical utilitarian welfare function and $\gamma = 1$ is associated with the Bernoulli-Nash function, while $\gamma \to \infty$ represents the maximin case. However what value[2] to choose for e ? Pearce (2003) suggests a simple way, in case of the classical utilitarian welfare function, for estimating the value of e. He judges the value of e by employing equity weights in order to evaluate the climate

[1] The reason why I do not use bigger values than 2 for γ is clarified in Footnote (5).

[2] Evans (2005) calculates the values of elasticity of marginal utility e for 20 OECD countries based on a tax-model. However, I am going to focus on a relation between e and γ in stead of merely value of e.

damages between poor and rich regions:

$$D_{WORLD} = D_p \left(\frac{\bar{Y}}{Y_p}\right)^e + D_r \left(\frac{\bar{Y}}{Y_r}\right)^e \tag{6.3}$$

Y is income, $\bar{Y}$ is the average world per-capita income, P and R refers to poor and rich regions, D is damage, and e is the elasticity of the marginal utility of income, $\left(\frac{\bar{Y}}{Y_p}\right)^e$, $\left(\frac{\bar{Y}}{Y_r}\right)^e$ are the equity weights for evaluating the damage in poor and rich regions. In equation (6.3) all damages are considered but the damage happened to developing countries (with incomes lower than world average) attracts higher weights than the damages in developed countries (with incomes higher than world average). One can judge the value of e by estimating the ratio of weights between poor and rich in equation (6.3) (that equals the ratio of the marginal utilities between poor and rich if the utility function of rich and poor are expressed by equation (6.1)) which is given by:

$$\left(\frac{\bar{Y}}{Y_p}\right)^e / \left(\frac{\bar{Y}}{Y_r}\right)^e = \left(\frac{Y_r}{Y_p}\right)^e$$

Assume $Y_R = 10Y_P$ is the case for international real-income comparisons between high income countries and low income countries. At $e = 1$, unit damage to the poor (or a marginal unit of income) is valued ten times the unit damage of the rich; if $e = 2$, the relative valuation is 100 times. On these simple calculation basis, values even of $e = 2$ are not justified. The apparent consensus in the literature (Clarkson and Deyes, 2002; Pearce and Ulph, 1999; Cowell and Gardiner, 1999; Cline, 1992) on the value of e is $1 < e < 1.5$, although Pearce and Ulph (1994) suggest $e = 0.8$ by using household behavior models. What values can γ take? Firstly, note that γ must be integer in order to make possible for welfare function to take real values and not complex ones. When $e > 1$ utility function takes negative values which implies that γ will be the equality aversion parameter in stead of the inequality aversion one (Azar, 1999). The values for γ will be found by developing in the next subsection a relation between e and γ (Fankhauser et al., 1997; Stenman, 2000).
Equity weights can also be derived by totally differentiating the social welfare function(Ray, 1984; Stenman, 2000):

$$dW = \sum_{i=1:n} \frac{\partial W}{\partial u_i} \frac{du_i}{dy_i}\, dY_i = \sum_{i=1:n} q_i\, dY_i \tag{6.4}$$

where equity weights q_i are:

$$q_i = \frac{\partial W}{\partial u_i} \frac{du_i}{dY_i} = \begin{cases} u_i^{-\gamma} Y_i^{-e}\,, & e \neq 1 \quad \forall i \\ u_i^{-\gamma} Y_i^{-1}\,, & e = 1 \quad \forall i \end{cases} \tag{6.5}$$

Equity weights must be used as the utility function can be concave in income, so that for the same income variation, utility changes more for a poor than for a rich person; alternatively, the social welfare function may be concave in utilities, so that the same utility variation from a low level, changes the social welfare more than the same utility variation from a high level.

6.2.1 Monetary Evaluation for Environmental Quality

One of the most debated issues related to the cost-benefit analysis (CBA) is the fact that the economic value of the environmental quality can be lower in poorer countries in comparison to richer ones due to positive income elasticity for risk reductions, if one does not apply any distributional weights. The condition for an equal monetary value of environment between poor and rich regions (or any other good like value of statistical life (VOSL)) to be used in a CBA can be written as follows (Fankhauser et al., 1997; Stenman, 2000):

$$\frac{\partial W}{\partial u_r} \frac{du_r}{dY_r} V_r = \frac{\partial W}{\partial u_p} \frac{du_p}{dY_p} V_p \Longleftrightarrow q_r V_r = q_p V_p \tag{6.6}$$

where V_r, V_p are values of environmental quality in rich and poor regions, and q_r, q_p are equity weights for rich and poor regions. After replacing in the equation (6.6), the derivative from equation (6.1) and equation (6.2), and noting that $V_r/V_p = (Y_r/Y_p)^\varepsilon$ where ε is the income elasticity of demand for environmental equality, it results:

$$\gamma = \frac{(e - \varepsilon)\, ln(Y_p/Y_r)}{ln(u_r/u_p)} \tag{6.7}$$

γ has to be integer in order to ensure that welfare function takes real values (and not complex ones). It implies that it makes sense to have e as a function of γ:

$$e = \gamma \, \frac{ln(u_r/u_p)}{ln(Y_p/Y_r)} + \varepsilon \tag{6.8}$$

I am going to perform a simple sensible analysis of equation (6.8). The income elasticity of demand ε in equation (6.8) is upper bound for e; when $\gamma = 0 \Longrightarrow e = \varepsilon$; when γ increases (keeping other parameters unchanged) e decreases as[3] $\frac{ln(u_r/u_p)}{ln(Y_p/Y_r)} < 0$. Therefore, it makes sense to support values of $\varepsilon = 1.2$ which gives γ a chance of being bigger than 1 in spite of, there are evidences that the ε can take also values of 0.33. The numerical computations, by letting values of $\gamma = \{0, 1, 2\}$[4], $Y_r/Y_p = \{3, 4, 5\}$ and $u_r/u_p = \{1.2, 1.3, 1.4\}$, show that the value of $e \in [0.8, 1.2]$, see Tables 6.1, 6.2, 6.3 and 6.4 in Appendix[5] one. The advantages of the numerical experiment above arise when there are only two types of countries, rich and poor. As the same social welfare function is used for both types of countries, then it is possible to find which values (or intervals) to use for e and γ in order to obtain smaller variation for optimal abatement levels.

6.3 Allocation Model of Burden Sharing Emissions

The cost (benefit) functions from relative abatements levels for every world region (or region) i are taken from two different models which are: the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model developed by Richard Tol[6];the MITs Emissions Prediction and Policy Analysis (EPPA) model developed at MIT[7]. Two optimization problems are constructed for cost functions specified by different models: one without emissions trading and one with emissions trading. The optimization problems are solved by using the MATLAB Optimization Toolbox[8]. The variables of first optimization problem are: R_i's relative abatements levels for every world region i; the variables of second optimization problem are again R_i's; the relative permissions levels for every world region i are equal to $(R(i) - R0)$ where $R_0 = 0.2$. The optimization problem without emissions trading is stated below:

$$\max \sum_{i=1:n} SWF_i \tag{6.9}$$

$$\sum_{i=1:n} R_i \geq R_k{}^9 \tag{6.10}$$

$$-1 \leq R_i \leq 1 \tag{6.11}$$

where SWF_i is the social welfare functions for each region i. Let have:

$$(Z_i = GDP_i + B_i - C_i)/POP_i \tag{6.12}$$

where GDP_i are Gross Domestic Production for every region i, $B_i = f(R_i), C_i = f(R_i)$ are the benefit[10] and cost function for every region i, and they are function of the relative abatement level of region i, R_i. The costs and benefits from pollution abatements are calculated for the year 2010 which is considered as the representative year of the first commitment period of the Kyoto protocol that includes the years 2008 through 2012. The Social Welfare Function (SWF) for each world region i is defined as:

$$SWF_i = POP_i \, \frac{\left(\dfrac{Z_i}{(1-e)}^{(1-e)} \right)^{(1-\gamma)}}{(1-\gamma)} \qquad \forall \, e \neq 1, \forall \, \gamma \neq 1 \tag{6.13}$$

[3] $\frac{ln(u_r/u_p)}{ln(Y_p/Y_r)} < 0$ as $ln(Y_p/Y_r) < 0, \;\; ln(u_p/u_r) > 0$ for $Y_p < Y_r, \;\; u_p < u_r$

[4] $\gamma = \{0, 1, 2\}$ means $\gamma = 0$, $\gamma = 1$, $\gamma = 2$.

[5] When $\gamma = \{3, 4\}$ the value of e goes down to 0.58. Therefore, those values of γ are considered as too high.

[6] See Yang et al. (1996) for a description of the EPPA model.

[7] See Link and Tol (2004) and http://www.fnu.zmaw.de/FUND.5679.0.html for a description of the FUND model.

[8] Computing programs can be provided on request.

[9] The value of $R_k = 3.2$ is taken. Note that, as the abatement levels of individual regions are finally estimated as fractions of the global abatement levels and not in absolute terms, the selected value for R_k (also for the next optimization problem) is not crucial.

[10] The benefit function from pollution abatement are provided only from the FUND model, while the cost function from pollution abatement are provided from both models FUND and EPPA.

$$SWF_i = POP_i \frac{\left(logZ_i\right)^{(1-\gamma)}}{(1-\gamma)} \qquad e = 1, \forall\, \gamma \neq 1 \tag{6.14}$$

$$SWF_i = POP_i\; log\left(\frac{Z_i}{(1-e)}^{(1-e)}\right) \qquad \forall\, e \neq 1, \gamma = 1 \tag{6.15}$$

$$SWF_i = POP_i\; log\,(logZ_i) \qquad e = 1, \gamma = 1 \tag{6.16}$$

Without constraints on the trading volumes, individually rational countries that maximize their utility of per capita income, will reduce their carbon emissions up to the point where their marginal abatements costs are exactly equal to the market price $C^{'}(R_i) = Pr$. This condition defines the emission reduction supply curve $RSi(Pr) = C^{'-1}(Pr)$. The market clearing price is defined as the price for which total supply is sufficient to achieve the emissions reduction constrain $RSi(Pr) = C^{'-1}(Pr) = 3.2$. The optimization problem with emissions trading is stated below:

$$\max \sum_{i=1:n} SWF_i \tag{6.17}$$

$$\sum_{i=1:n} R_i = 3.2 \tag{6.18}$$

$$\sum_{i=1:n} RS_i(Pr) = 3.2 \tag{6.19}$$

$$lb \leq R_i \leq ub \tag{6.20}$$

$$0 \leq Pr \leq 1000 \tag{6.21}$$

The optimization problem 6.17 has the same welfare function SWF, which is defined in equations (6.13), (6.14), (6.15) and (6.16), but Z_i is defined differently:

$$Z_i = (GDP_i + B_i - C_i + Pr(R_i - R_0)E_i)/POP_i \tag{6.22}$$

The price of selling (when selling $R_i < R_0$, when buying $R_i > R_0$) of 1 ton emissions equals Pr Dollars, which changes income by $Pr(Ri - R0)Ei$ (when emission permits are bought or sold), and changes also emissions cost, which is reflected at the cost function C_i.
The FUND model distinguishes 16 major regions of the world, viz. the United States of America (USA), Canada (CAN), Western Europe (WEU), Japan and South Korea (JPK), Australia and New Zealand (ANZ), Central and Eastern Europe (EEU), the former Soviet Union (FSU), the Middle East (MDE), Central America (CAM), South America (LAM), South Asia (SAS), Southeast Asia (SEA), China (CHI), North Africa (NAF), Sub-Saharan Africa (SSA), and Small Island States (SIS). The benefit B and the cost C of a country (region) i in the FUND model are given as:

$$B_i - C_i = \beta_i \sum_{j}^{n} R_j E_j - \alpha_i R_i^2 Y_i \tag{6.23}$$

where R denotes relative emission reduction, β marginal damage costs of carbon dioxide emissions, E unabated emissions, Y gross domestic product, indexes i denote regions and α is the cost parameter, see Table 6.5.
The regions in EPPA model are United States of America (USA), Japan (JPN), European Union (EEC, EC-12 as of 1992), Other OECD Countries (OOE), Eastern Europe (EET), Former Soviet Union (FSU), Energy Exporting Countries (EEX), China (CHN), India (IND), Dynamic Asian Economies (DAE), Brazil (BRA) and Rest Of World (ROW). The cost C of a country (region) i in the EPPA model are given as:

$$C_i = 1/3a_i(R_iE_i)^3 + 1/2b_i(R_iE_i)^2 \tag{6.24}$$

where R denotes relative emission reduction, a and b are the cost parameters, and E are the unabated emissions, see Table 6.6.

The world regions for two models FUND and EPPA can be fairly approximated by two types, OECD countries (or rich ones) and non-OECD countries (or poor ones)[11]. The social welfare function of the same shape is used for both types of countries. The values (or intervals) of the elasticity of marginal utility e and the inequality aversion parameter γ are taken from Tables 6.1, 6.2, 6.3 and 6.4 in Appendix which make use of the equation 6.8. The relation between e and γ allows to narrow the variation of e for a specific value of γ. As a consequence it is possible to attain smaller variation for the optimal emissions reduction levels too.
Four different types of optimization problem are considered, the first two ones are FUND (FUND-1) model and EPPA (EPPA-1) without a permit system. The comparison between the FUND-1 and EPPA-1 is postponed to Appendix two, as the main purpose of comparing them, is to point out that the results are robust. The upper and low bounds of abatement variables for the first two optimization problem are tightened. If the bounds of variables are not contracted then the optimization for EPPA-1 shifts all the abatement weight to region OOE (Other OECD Countries) as they have a negative parameter (the parameter b) of cost calculation in the equation 6.24, which makes the results unreliable.
The last two models are, the FUND model without permits system (FUND-2), and the FUND model with permits system (FUND-permit). The comparison between the FUND-2 and FUND-permit are presented in the next section.

6.4 Results, FUND with permits and without permits system

The results of the FUND model without permits system (FUND-2) and with permits system (FUND-permit) are discussed. The abatement levels are estimated as fractions of the global abatement levels. It means that I focus in the fraction of abatement levels that a region (like European Union) is undertaking but not in the absolute amount of it.
The results of FUND-2 are presented in Table 6.7 and in Figures 6.1, 6.3 and 6.5 while the results of FUND-permit are presented in Table 6.8 and in Figures 6.2, 6.4 and 6.6. Tables 6.7 represents all regions and their optimal abatement levels; different values of the elasticity of marginal utility e different values of the inequality aversion parameter γ are taken into account which respect the relation of e and γ originating from equation 6.8. The Figures[12] introduce the optimal abatement levels for rich and poor regions for γ equal to 0, 1 and 2 and $e \in (0, 1.5)$. The most reliable intervals of e for every specific γ are explained in every figure.
In both models approach (with and without permits system), the abatement levels of poor countries are different from zero as Kyoto protocol assigns. It implies that Kyoto protocol assigns a peculiar value of the elasticity of marginal utility e for every γ which exceeds the value of 1.5 (see Figures from 6.1 to 6.6). The peculiar choose of e for every γ leads to a selection of abatement levels which are not optimal. Former Soviet Union has to abate pollution in large amounts, which is not foreseen in Kyoto protocol. All model approaches (EPPA-1, FUND-1, FUND-2 and FUND-permit) for every combination of parameters e and γ, predict that FSU has to play a central role in abatement policies among non-OECD countries. Therefore, it is considered as a robust result (see Tables 6.7 and 6.8).
FUND-permit is highly overestimating the optimal abatement level of Western European Union (by 132%). This result is also not robust as FUND-1 and EPPA-1 estimate the optimal abatement level of WEU similar to USA (EPPA-1 even lower than USA and equal to Japan)). However, seeing beyond simple numbers, it is only a reinforcement that WEU is a key player in global abatement policies. USA has to undertake usually the highest abatement target (sometime WEU has higher abatement target) among all world regions which strengthens the conclusions that there is no successful climate change policy without USA. Japan (JPN) has to abate their pollution levels lower than USA and WEU but higher than any other country (except the FSU which surpass sometimes the abatement levels of Japan). Regions like Canada, Australia, China, India and East European Countries are changing their optimal

[11]Concerning FUND model, the world regions of United States of America (USA), Canada (CAN), Western Europe (WEU), Japan and South Korea (JPK), Australia and New Zealand (ANZ) are considered as OECD countries (or rich ones), and the rest of regions as non-OECD ones (or poor ones) while concerning EPPA model, world regions of United States of America (USA), Japan (JPN), European Union (EEC, EC-12 as of 1992), Other OECD Countries (OOE) are considered as OECD countries (or rich ones), and the rest of regions as non-OECD ones (or poor ones)

[12]Numerical instability is experienced for the single point $e = 1$ when $\gamma = 2$, therefore in Figures 6.5 and 6.6 a circle is placed in this particular point. However, the optimal abatement levels for the cumbersome point are presented in Tables 6.7 and 6.8, and they are consistent with conclusions. I think that the numerical instability is inherited from the shape of the social welfare function because the numerical experiments with the SWF for $e \neq 1$ (when $\gamma = 2$, see equation 6.13) and, $e = 1$ (when $\gamma = 2$, see equation 6.14) show that there is discontinuity for both types of functions for the neighborhood of particular point $e = 1$ (which must not be).

abatement levels in a wide range from very low (or even negative ones) to some considerable amounts which certify that it is hard based on available information, to assign those countries the "right" abatement level.

6.5 Conclusions

The paper examines if the abatement targets that Kyoto protocol assigns to different countries, are consistent with the normative requirement that environmental goods are valued equally in non-OECD (or poor) and OECD (or rich) countries. Several different global welfare maximization problems with permits system and without permits system are established, which are constrained to the same specific global abatement level. A wide range of social welfare functions is used such as the utilitarian ($\gamma = 0$), Bernoulli-Nash ($\gamma = 1$), and a special welfare function for $\gamma = 2$. In global welfare maximization problems, I make use of benefits and costs of pollution abatement for two different integrated assessment models, the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model developed by Richard Tol, and the MITs Emissions Prediction and Policy Analysis (EPPA) model developed at MIT.

By demanding that environmental goods are evaluated equally in non-OECD (or poor) and OECD (or rich) countries and using equity weights, a relation between the elasticity of marginal utility e and the inequality aversion parameter γ is set up. The relation helps us to contract the intervals of e for particular values of γ. Furthermore, it supports us to tighten the variation of optimal abatement levels when global social welfare is maximized.

It is found that the abatement targets of Kyoto protocol assume only a peculiar value for elasticity of marginal utility e for any possible given value of γ. This peculiar value of e produces no abatement level for developing countries which is not an optimal target. From the other side, the abatement levels for developed countries are correctly assigned. On the opposite the Former Soviet Union has to play a central role among developing countries which is not foreseen in Kyoto protocol. Regions like Canada, Australia, China, India and East European Countries are changing their optimal abatement levels in a wide range which indicates that it is difficult to assign an abatement target to those countries.

As always, further extensions are possible such as the implementation of dynamic framework for a longer time interval, or finding a way of including of political factors in modeling approach.

Acknowledgment

I am grateful to Richard Tol for his comments and suggestions.

Appendix 1

Table 6.1: The values of elasticity of marginal utility **e** for different values of γ, when $u_r/u_p = 1.2$, $Y_r/Y_p = 5$, $\varepsilon = 1.2$.

$\gamma = 0$	$\gamma = 1$	$\gamma = 2$
1.2	1.1408	1.0816

Table 6.2: The values of elasticity of marginal utility **e** for different values of γ and u_r/u_p, when $Y_r/Y_p = 5$, $\varepsilon = 1.2$.

	$\gamma = 0$	$\gamma = 1$	$\gamma = 2$
$u_r/u_p = 1.2$	1.2	1.0867	0.9734
$u_r/u_p = 1.3$	1.2	1.037	0.874
$u_r/u_p = 1.4$	1.2	0.9909	0.7819

Table 6.3: The values of elasticity of marginal utility **e** for different values of γ and Y_r/Y_p, when $u_r/u_p = 1.2$, $\varepsilon = 1.2$.

	$\gamma = 0$	$\gamma = 1$	$\gamma = 2$	$\gamma = 3$	$\gamma = 4$
$Z_r/Z_p = 3$	1.2	1.0685	0.937	0.8054	0.6739
$Z_r/Z_p = 4$	1.2	1.0982	0.9965	0.8947	0.793
$Z_r/Z_p = 5$	1.2	1.117	1.034	0.9511	0.8681

Table 6.4: The values of elasticity of marginal utility **e** for different values of γ, Z_r/Z_p and u_r/u_p, when $\varepsilon = 1.2$.

	$\gamma = 0$	$\gamma = 1$	$\gamma = 2$	$\gamma = 3$	$\gamma = 4$	
$Z_r/Z_p = 3$	1.2	1.0685	0.937	0.8054	0.6739	$u_r/u_p = 1.2$
$Z_r/Z_p = 4$	1.2	1.0536	0.9071	0.7607	0.6143	$u_r/u_p = 1.3$
$Z_r/Z_p = 5$	1.2	1.0469	0.8937	0.7406	0.5875	$u_r/u_p = 1.4$

Table 6.5: The FUND data from the year 2010, where α is the abatement cost parameter (unitless), β the marginal damage costs of carbon dioxide emissions (in dollars per tonne of carbon) E the carbon dioxide emissions (in billion metric tonnes of carbon), Y gross domestic product, in billions US dollars and population in millions people. Source: FUND

	α	β	E	Y	*Population*
USA	0.0152	2.0882	1.7315	11886	295.1
CAN	0.0152	0.0966	0.1315	93	33
WEU	0.0157	3.1036	0.786	14072	39.2
JPK	0.0156	-1.1404	0.5675	9829	185.7
ANZ	0.0151	-0.0257	0.0855	526	25.3
EEU	0.0147	0.1057	0.189	476	122.4
FSU	0.0138	1.1862	0.952	751	291.5
MDE	0.0144	0.1087	0.4875	742	292.2
CAM	0.0149	0.0833	0.126	456	155.5
LAM	0.0151	0.2542	0.2445	1578	390.7
SAS	0.0144	0.3678	0.6575	1064	1585.6
SEA	0.0149	0.7108	0.413	1432	600.8
CHI	0.0145	4.7834	1.6145	3085	1429.7
NAF	0.0147	0.8981	0.1105	261	176.5
SSA	0.0147	0.9469	0.157	374	810.1
SIS	0.0144	0.0627	0.0435	66	49.7

Table 6.6: The EPPA data from the year 2010, where a, b are the abatement cost parameters (in dollars per tonne of carbon, $a + b$ is the marginal damage costs of first tonne of carbon dioxide emissions), E the carbon dioxide emissions (in billion metric tonnes of carbon), Y gross domestic product, in billions US dollars and population in millions people. Source: EPPA and Weikard et al. (2006)

	a	b	E	Y	*Population*
USA	0.0005	0.0398	2.42	8845	305
JPN	0.0155	1.816	0.56	5584	124
EEC	0.0024	0.1503	1.4	9579	375
OOE	0.0085	-0.0986	0.62	1902	142
EET	0.0079	0.0486	0.51	405	120
FSU	0.0023	0.0042	1	501	287
EEX	0.0032	0.3029	1.22	1650	1602
CHN	0.0001	0.0239	2.36	1021	1340
IND	0.0015	0.0787	0.63	458	1145
DAE	0.0047	0.3774	0.41	972	207
BRA	0.5612	8.4974	0.13	774	190
ROW	0.0021	0.0805	0.7	1119	584

Table 6.7: Relative abatement levels (as ration of global abatement levels) for different world regions, FUND model without permits system (boundshigh, equal constrains)

	$\gamma = 0, e = 1.2$	$\gamma = 1, e = 0.9$	$\gamma = 2, e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
USA	0.62	0.34	0.62	0.46	1.95	0.25
CAN	-0.48	-0.13	-0.48	-0.28	-2.08	-0.03
WEU	1.52	0.85	1.52	1.19	2.5	0.56
JPK	0.22	0.13	0.22	0.17	1.25	0.1
ANZ	-0.74	-0.28	-0.74	-0.5	-2.18	-0.13
EEU	-0.05	-0.004	-0.05	-0.03	-0.54	0.02
FSU	0.2	0.19	0.2	0.19	0.15	0.19
MDE	0.06	0.07	0.06	0.06	0.31	0.07
CAM	-0.07	-0.03	-0.07	-0.05	-0.32	-0.01
LAM	-0.004	0.01	-0.004	0.002	0.03	0.01
SAS	0.02	0.02	0.02	0.02	0.003	0.02
SEA	0.02	0.02	0.02	0.02	0.03	0.03
CHI	0.07	0.07	0.07	0.07	0.06	0.07
NAF	-0.06	-0.03	-0.06	-0.05	-0.14	-0.01
SSA	-0.01	-0.003	-0.01	-0.01	0.07	0.001
SIS	-0.31	-0.21	-0.31	-0.27	-0.08	-0.15

Table 6.8: Relative abatement levels (as ration of global abatement levels) for different world regions, FUND model in a permits system (boundshigh, equal constrains)

	$\gamma = 0, e = 1.2$	$\gamma = 1, e = 0.9$	$\gamma = 2, e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
USA	0.6	0.34	0.6	0.45	2	0.23
CAN	-0.84	-0.43	-0.85	-0.63	-2.12	-0.3
WEU	1.32	0.63	1.32	0.96	2.33	0.39
JPK	0.13	0.09	0.13	0.1	0.57	0.07
ANZ	-1.09	-0.65	-1.09	-0.86	-2.12	-0.48
EEU	-0.04	0.01	-0.04	-0.01	-0.56	0.02
FSU	0.53	0.51	0.53	0.52	0.62	0.51
MDE	0.21	0.21	0.21	0.21	0.17	0.21
CAM	-0.07	-0.03	-0.07	-0.05	-0.35	-0.02
LAM	0.01	0.02	0.01	0.01	-0.17	0.02
SAS	0.18	0.19	0.18	0.18	0.18	0.19
SEA	0.08	0.08	0.08	0.08	0.06	0.08
CHI	0.21	0.21	0.21	0.21	0.23	0.2
NAF	-0.01	0.01	-0.01	0.003	0.03	0.02
SSA	0.1	0.1	0.1	0.1	0.08	0.1
SIS	-0.31	-0.26	-0.31	-0.28	0.05	-0.25

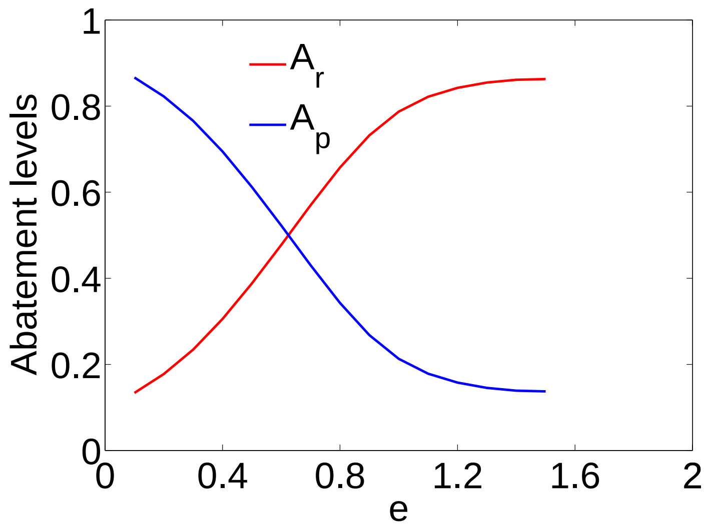

Figure 6.1: The relation between fractional abatement levels A (for poor countries A_p and for rich countries A_r) and values of elasticity of marginal utility e when $\gamma = 0$ without permit trading system, FUND model. Note that when $\gamma = 0$, e = 1.2 so values of A corresponding to e = 1.2 are considered as more realistic.

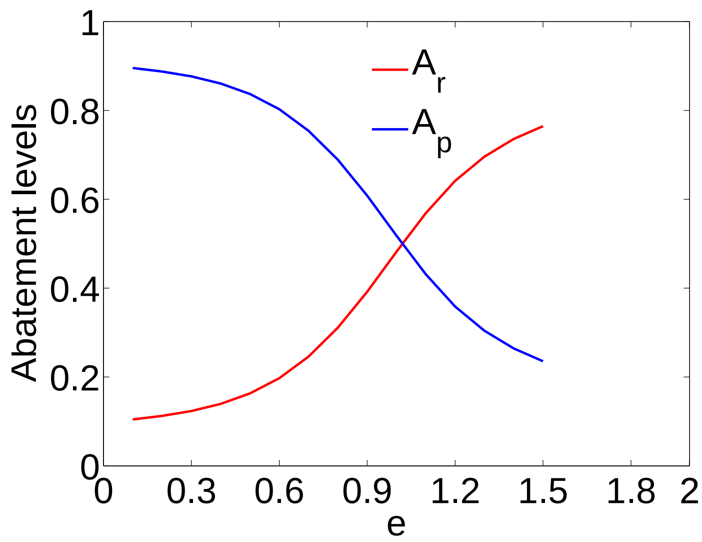

Figure 6.2: The relation between fractional abatement levels A (for poor countries A_p and for rich countries A_r) and values of elasticity of marginal utility e when $\gamma = 0$ in permit trading system, FUND model. Note that when $\gamma = 0$, e = 1.2 so values of A corresponding to e = 1.2 are considered as more realistic.

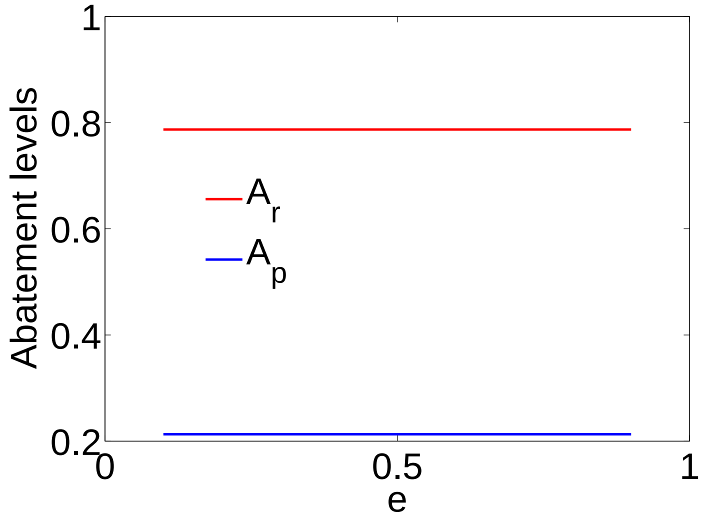

Figure 6.3: The relation between fractional abatement levels A and values of elasticity of marginal utility e when $\gamma = 1$ without permit trading system, FUND model. Note that when $\gamma = 1$, $e \in (0.99, 1.1)$ so values of E corresponding to $e \in (0.78, 1.08)$ are considered as more realistic.

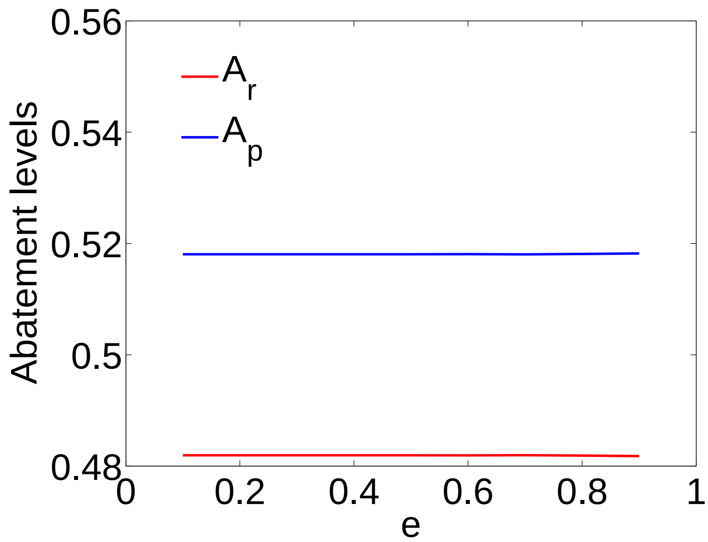

Figure 6.4: The relation between fractional abatement levels A and values of elasticity of marginal utility e when $\gamma = 1$ in permit trading system, FUND model. Note that when $\gamma = 1$, $e \in (0.99, 1.1)$ so values of E corresponding to $e \in (0.78, 1.08)$ are considered as more realistic.

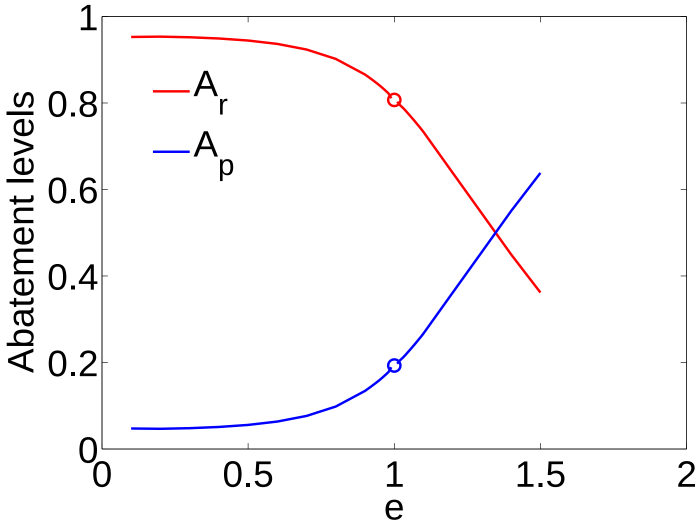

Figure 6.5: The relation between fractional abatement levels A and values of elasticity of marginal utility e when $\gamma = 2$ without permit trading system, FUND model. Note that when $\gamma = 2$, $e \in (0.78, 1.08)$ so values of E corresponding to $e \in (0.78, 1.08)$ are considered as more realistic.

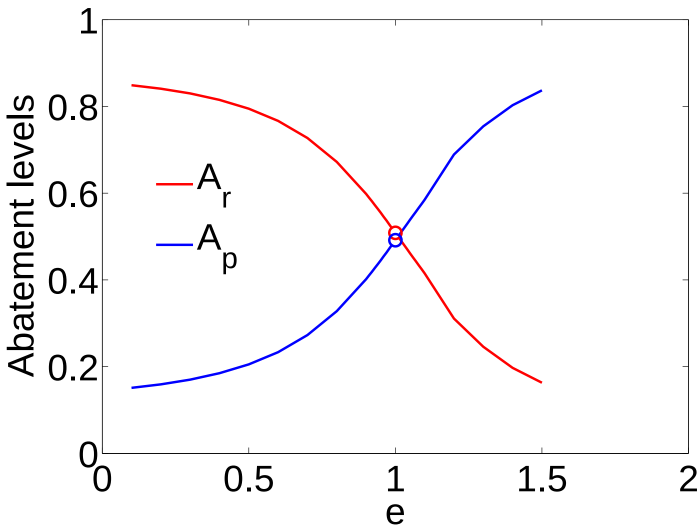

Figure 6.6: The relation between fractional abatement levels A and values of elasticity of marginal utility e when $\gamma = 2$ in permit trading system, FUND model. Note that when $\gamma = 2$, $e \in (0.78, 1.08)$ so values of E corresponding to $e \in (0.78, 1.08)$ are considered as more realistic.

Appendix 2

6.5.1 Comparing results for FUND and EPPA models without permits

The first optimization problem is primarily used in order to make clear that results are robust as estimations from two different models FUND and EPPA display similarities[13].
Table 6.9, Figures 6.7, 6.9 and 6.11 present the results for FUND model while Table 6.10, Figures 6.8 and 6.10 present the results for EPPA model. Tables 6.9 represent all regions and their optimal abatement levels (for FUND model) for values of the elasticity of marginal utility e that corresponds to the values of inequality aversion parameter γ (according to relation of e and γ from equation 6.8). The Figures[14] introduce the optimal abatement levels for rich and poor regions for γ equal to 0, 1 and 2 and $e \in (0, 1.5)$. The most reliable intervals of e for every γ that equals 0, 1 and 2 are given for every figure.
The results demonstrate similar pattern, namely the abatement levels of rich countries are higher than those of poor countries (see Figures from 6.7 to 6.10 and Tables 6.9 and 6.10). But the abatement levels of poor countries are not zero. The FUND model predicts that the optimal abatement levels of poor countries are in the range of 37 % to 50 % of the total global level, while the EPPA model predicts that the optimal abatement levels of poor countries are in the range from 11 % to 46 % of the total global level. The models affirm that the Kyoto protocol assigns a peculiar value to the marginal elasticity of substitution e for any value of the inequality aversion parameter γ, which advices no abatement efforts for poor countries. Both models also forecast that the Former Soviet Union (FSU) must have a high abatement level which anticipates the Kyoto target for FSU. They assign to China (respectively 2% and 0.2%) and India (respectively 1% and 0.4%) low abatement targets.
The main difference between models is that EPPA assigns to other OECD countries (OOE where Canada and Australia are essential players) a high abatement level of 42%, while FUND assigns to Canada and Australia together only 24%. Other differences, the changes in abatement levels for Western European Union, Japan and Eastern European Countries.

[13] When comparing FUND with EPPA, I use lower bounds equal to -1, while upper bounds equal to 1. Those bounds are used as EPPA models shifts all abatement burdens to region OOE (other OECD countries) as they have partly benefits from pollution abatement (the parameter cost b is negative, see Table 6.6).

[14] Numerical instability is experienced for the single point $e = 1$ when $\gamma = 2$ for FUND model, and for the interval $e \in (0.8, 1.08)$ when $\gamma = 2$ for EPPA model. Therefore, a circle is placed in the point $e = 1$ in Figures 6.11. This happens, as already clarified in Footnote 12, because the shape of Social Welfare Function with two parameters (e and γ) behaves inappropriately at the point $e = 1$ (when $gamma = 2$). We experience numerical instability when $\gamma = 2$, which is located in an interval (not in a single point) for EPPA model. The stopping criteria for the optimization problem are sufficiently small (around 10^{-19}), which help to think that the numerical instability occurs because the variation of the optimal abatement levels is very sensible to the variations of elasticity of marginal utility e. There is no Figure for EPPA model when $\gamma = 2$, but the results of optimization problem are shown in the Table 6.10. Anyway, the variation of the optimal abatement levels stays in an interval that makes possible to claim that the EPPA results have a similar pattern with FUND, and therefore, are still robust.

Table 6.9: Relative abatement levels (as ration of global abatement levels) for different world regions, FUND model, second optimization problem without permits system (boundslow)

	$\gamma = 0, e = 1.2$	$\gamma = 1, e = 0.9$	$\gamma = 2, e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
USA	0.12	0.13	0.12	0.13	0.1	0.15
CAN	0.12	0.13	0.12	0.13	0.1	0.1
WEU	0.12	0.13	0.12	0.13	0.1	0.17
JPK	0.12	0.1	0.12	0.12	0.1	0.07
ANZ	0.12	0.11	0.12	0.12	0.1	0.09
EEU	0.05	0.05	0.05	0.05	0.1	0.05
FSU	0.11	0.11	0.11	0.11	0.1	0.12
MDE	0.05	0.05	0.05	0.05	0.08	0.06
CAM	0.03	0.03	0.03	0.02	0.05	0.03
LAM	0.02	0.02	0.02	0.02	0.06	0.02
SAS	0.01	0.01	0.01	0.01	0.004	0.02
SEA	0.02	0.02	0.02	0.02	0.03	0.02
CHI	0.04	0.04	0.04	0.03	0.04	0.04
NAF	0.02	0.02	0.02	0.02	0.01	0.02
SSA	0.004	0.01	0.004	0.01	0.01	0.01
SIS	0.02	0.03	0.02	0.03	0.004	0.03

Table 6.10: Relative abatement levels (as ration of global abatement levels) for different world regions, EPPA model, second optimization problem without permits system (boundslow)

	$\gamma = 0, e = 1.2$	$\gamma = 1, e = 0.9$	$\gamma = 2, e = 0.8$	$e = 0.9$	$e = 1$	$e = 1.1$
USA	0.1	0.1	0.06	0.11	0.07	0.06
JPN	0.06	0.06	0.07	0.06	0.27	0.03
EEC	0.06	0.07	0.08	0.03	0.13	0.04
OOE	0.42	0.31	0.39	0.42	0.42	0.42
EET	0.14	0.17	0.16	0.14	0.05	0.16
FSU	0.15	0.2	0.17	0.18	0.02	0.21
EEX	0.0006	0.001	0.002	0.0004	0	0.001
CHN	0.002	0.002	0.002	-0.003	0	0.003
IND	0.004	0.01	0.001	0.01	0.0002	0.01
DAE	0.04	0.04	0.04	0.02	0.03	0.03
BRA	0.01	0.01	0.01	0.01	0.01	0.01
ROW	0.02	0.03	0.005	0.01	0.005	0.03

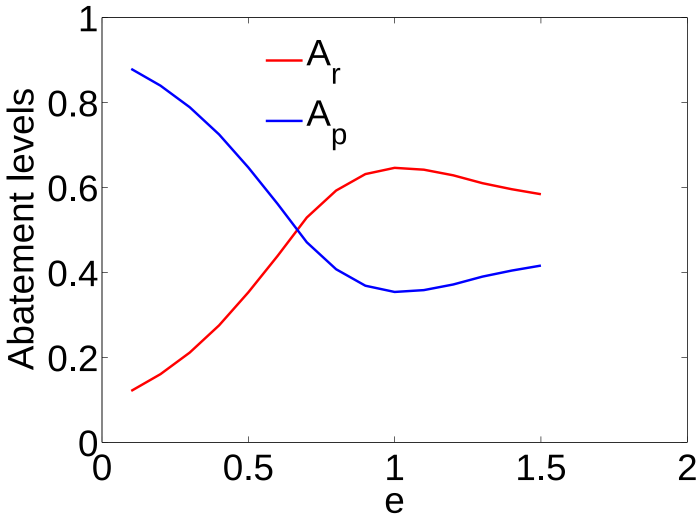

Figure 6.7: The relation between fractional abatement levels A (for poor countries A_p and for rich countries A_r) and values of elasticity of marginal utility e when $\gamma = 0$, FUND model. Note that when $\gamma = 0$, e $= 1.2$ so values of A corresponding to e $= 1.2$ are considered as more realistic.

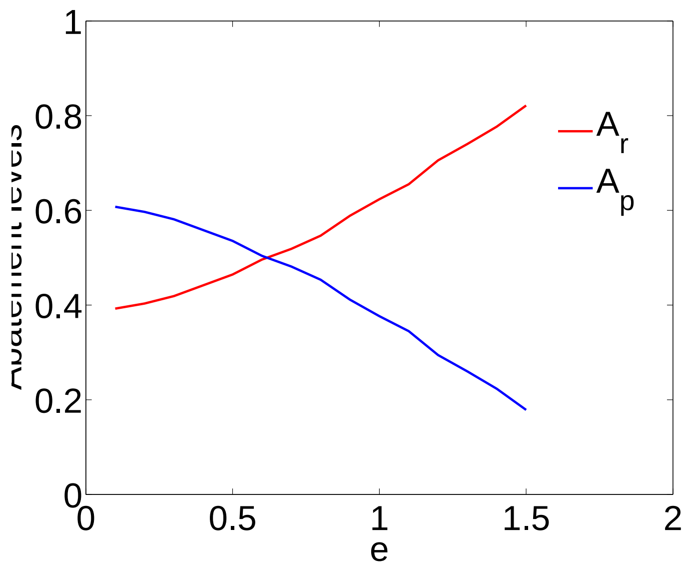

Figure 6.8: The relation between fractional abatement levels A (for poor countries A_p and for rich countries A_r) and values of elasticity of marginal utility e when $\gamma = 0$, EPPA model. Note that when $\gamma = 0$, e $= 1.2$ so values of A corresponding to e $= 1.2$ are considered as more realistic.

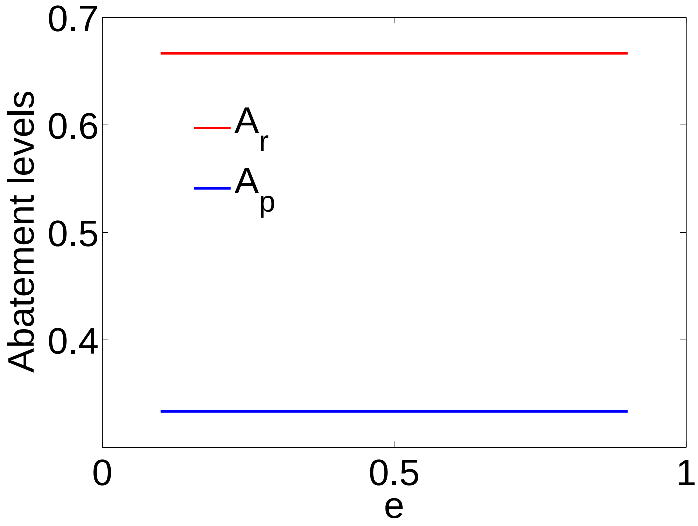

Figure 6.9: The relation between fractional abatement levels A and values of elasticity of marginal utility e when $\gamma = 1$, FUND model. Note that when $\gamma = 1$, $e \in (0.99, 1.1)$ so values of E corresponding to $e \in (0.78, 1.08)$ are considered as more realistic.

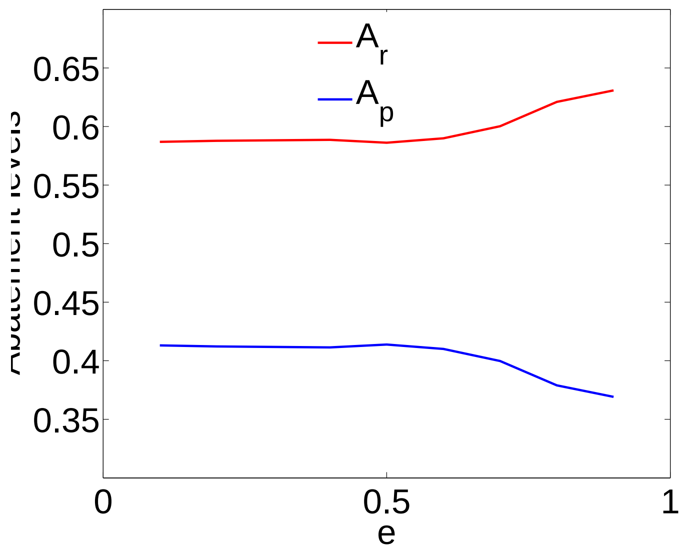

Figure 6.10: The relation between fractional abatement levels A and values of elasticity of marginal utility e when $\gamma = 1$, EPPA model. Note that when $\gamma = 1$, $e \in (0.99, 1.1)$ so values of E corresponding to $e \in (0.78, 1.08)$ are considered as more realistic.

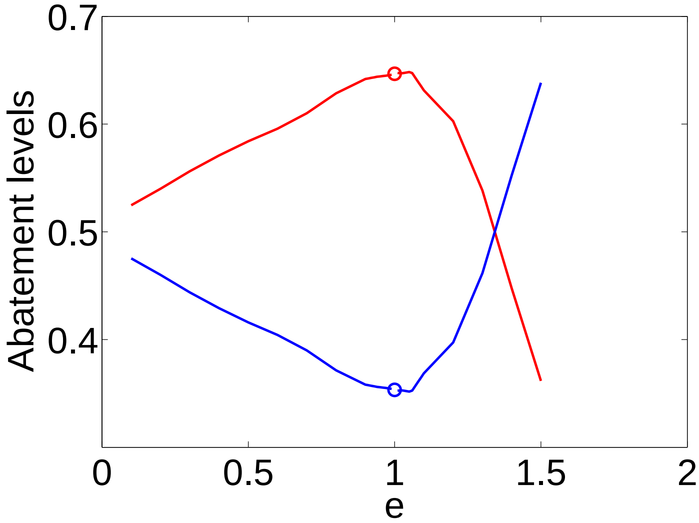

Figure 6.11: The relation between fractional abatement levels A and values of elasticity of marginal utility e when $\gamma = 2$, FUND model. Note that when $\gamma = 2$, $e \in (0.78, 1.08)$ so values of E corresponding to $e \in (0.78, 1.08)$ are considered as more realistic.

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Summary of Conclusions

The research analyzes the stability and burden sharing emissions in international environmental agreements (IEA).

The first paper investigates the size and the improving capability of two self-enforcing IEA. An IEA is self-enforcing when no country wants to withdraw and no country wants to join the IEA. As we employ a simplified model the results must be interpreted with caution. Although our work is less general than that of Yi and Shin, Bloch etc, we are able to compute the coalition sizes and optimal abatement levels.
We find that adding a second coalition improves welfare and environmental quality when the number of players is small and cost of pollution is high. That is, multiple coalitions help with continental environmental problems, but not with global environmental problems. At first sight, this conclusion is counterintuitive. Surely, bigger problems require a larger number of coalitions? However, the intuition behind the result follows from Barrett's (1994) analysis. Barrett (1994) shows that stable coalitions are either small or irrelevant. "He also shows" / "Here we extend that result to show" that the share of players that cooperate grows if the number of players fall.
Consider a serious environmental problem with a large number of players. According to Barrett (1994), only a small coalition would form. If we take the cooperative players out of the population, we are left with a still large number of players with a still serious environmental problem. In this subpopulation, only a small coalition would form. So, a second coalition does not add much. In fact, the additional constraint of inter-coalition stability more than offsets the gains of cooperation in the second coalition.
Now consider a serious environmental problem with a medium number of players. According to Barrett (1994), only a small coalition would form. If we take these players out of the population, we are left with smaller number of players with a considerable environmental problem. In this subpopulation, a larger coalition would form. That is, a second coalition does improve welfare and environmental quality. In this case, the inter-coalition stability constraint reduces but not eliminates these gains.
If this intuition is correct, one may suspect that an environmental problem with a large number of players requires a high number of coalitions – and that only the "last" coalition will contribute to gains in welfare and environmental quality. However, with every additional coalition, the number of inter-coalition stability constraints grows combinatorially. This would offset these gains, and limits the number of coalitions that can form. This problem is deferred to future research.
The first paper considers stylized cost-benefit functions and identical countries which are the main shortcomings of this research. These shortcomings are overcome in the second paper where cost-benefit functions from FUND (developed by Richard Tol) are used, and different world regions are considered (thus not identical).

The second paper examines the problem of deriving the size of farsightedly stable IEAs under a complex stability concept, namely farsighted stability. The FUND model provides the cost-benefit function of pollution abatement (*also for third, forth and fifth paper*). It is clear that the dynamic of damage-cost functions of the FUND model determines the results.
The D'Aspremont stability concept, which assumes that the players are myopic and consider only single-player movements, is very restrictive. Instead, the farsightedly stability concept is used. Farsighted stability implies that if a country considers deviating, it will realize that a deviation may trigger further deviations, which can worsen the country's initial position. All farsightedly stable coalitions are found by using simple combinatorial algorithms. As it is usually true (for FUND model is always true) that farsightedly stable coalitions must be profitable, a significant reduction of computational effort is achieved. We refine and improve further the farsighted stability concept to preferred farsighted stability. Preferred farsightedly stable coalitions can more likely form from a usual starting state, such as the atom

structure, in comparison to other farsightedly stable coalitions.
The D'Aspremont stability and farsighted stability concepts, surprisingly seem to reach one similar conclusion, namely that the size of a single stable coalition is relatively small. D'Aspremont stability argues that the free-riding makes it difficult to have large single stable coalitions. In contrast, with farsighted stability, coalition size is limited by the constraint that a coalition must be profitable. In addition, the asymmetry of countries makes the profitability condition difficult to fulfil and prevents large farsightedly stable coalitions. Nevertheless, single farsightedly stable coalitions clearly improve the welfare and abatement level in comparison to D'Apremont stable coalitions.
We consider also multiple farsightedly stable coalitions, which leads to an optimistic result. Almost 70 % of all regions can cooperate and improve welfare and environmental quality significantly. We show that multiple farsighted coalitions have a clear advantage compared to multiple D'Apremont stable coalitions.

The third paper extends further the research of the second one by investigates carefully the differences between farsighted stability and D'Aspremont stability.
All farsightedly stable and D'Aspremont stable coalitions are found and their improvements to welfare and environmental equality. There are a lot more farsighted stable coalitions than D'Apremont stable coalitions, so the farsighted stability enlarges the space of cooperation.
Here, we find not only preferred farsighted coalitions but also preferred D'Aspremont stable coalitions. We argue that D'Aspremont stability is myopic in two senses. Firstly, because it considers only single-player movements. Secondly, because the internal D'Aspremont stability requests no free-riding. Nevertheless, no free-riding means that improvements (in welfare and environmental equality) from cooperation are small. Therefore, the internal D'Aspremont stability indirectly requests that the improvements from cooperation are small.
The size of largest single farsightedly stable coalition and D'Aspremont stable coalition is small. The D'Aspremont stability argues that the free-riding makes difficult to have large single stable coalitions. On the opposite the farsighted stability argues that due to the asymmetry, the profitability condition is hard to be satisfied for large single farsightedly stable coalitions. Moreover, the asymmetry of countries makes profitability condition hard to be realized and avoids maintaining big farsightedly stable coalitions. In spite of single D'Aspremont coalitions are very small (only three countries) they bring improvement in comparison to atom structure. However, the farsightedly stable coalitions improve the welfare and environmental equality in comparison to D'Aspremont stable coalitions.
We show that the D'Aspremont stable coalitions are often sub-coalitions of farsightedly stable coalitions. Moreover, farsightedly stable coalitions can be frequently the biggest size stable coalition. Furthermore, they produce always the biggest improvement in environmental and welfare that game theory without side payments can attain.
By considering the multiple farsightedly stable coalitions leads to an optimistic result of game theory. More than two thirds of regions (around 40 % of countries cooperate in case of multiple D'Apremont stable coalitions) can cooperate and improve significantly the welfare and environmental quality. The multiple D'Aspremont stable coalitions significantly improve the welfare in comparison to atom structure behavior. However, the multiple farsightedly stable coalitions clearly increase the welfare and abatement levels compare to multiple D'Aspremont stable coalitions.

The forth paper analyzes the problem of evolution of farsightedly stable coalition for different time horizons. Clearly the profit functions of pollution abatement consider only economic incentives.
The number of farsightedly stable coalitions is big especially for last time horizons, this implies that there are a lot of countries which have economic incentives to join international environmental agreements like Kyoto protocol in a "farsighted world". There are two preferred farsightedly stable coalitions for each time horizons which include more than two thirds (from eleven to fourteen) of sixteen world regions, and they improve substantially the welfare and abatement levels compare to atom structure.
The farsighted stability is fragile with respect to small variations in parameters and circumstances. In order to have robust farsightedly stable coalitions for different time horizons, one needs to keep the emissions of each coalition member and the variation of marginal benefits from pollution abatement among coalition members as low as possible. However, emissions and marginal benefits from pollution abatement are determined by rate of economic growth of each country and cannot be controlled. Furthermore, the members and size of farsightedly stable coalitions are very sensible to the emissions variation of certain coalition members from one year horizon to the future one. Then, it follows that farsightedly stable coalitions cannot be sustained for long terms, which implies that the "selfish farsighted world" can assure only temporary big international coalitions.

The literature in international environmental agreements supposes that countries within a coalition maximize their joint welfare while the single countries play non-cooperatively against the coalition and against each-other. The fifth paper investigates if joint welfare maximization shares the welfare level fairly among coalition members. The joint welfare maximization is compared to classical cooperative game value like Shapley Value, Nash bargaining solution and Consensus Value for four different coalitions. The Nash bargaining solution gives similar solution compared to joint welfare maximization. The Shapley Value and Consensus Value differ significantly compared to joint welfare maximization. One can consider the joint welfare maximization as reasonable assumption as it is similar also with another well-known scheme such as Nash Bargaining solution. Further work is needed in considering more coalitions and approaches that are more general.

The last paper examines if the abatement targets that Kyoto protocol assigns to different countries, are consistent with the normative requirement that environmental goods are valued equally in non-OECD (or poor) and OECD (or rich) countries. We establish several different global welfare maximization problems with permits system and without permits system constrained to the same specific global abatement level. A wide range of social welfare functions is used such as the utilitarian, Bernoulli-Nash, and maximin. In our global welfare maximization problems, we make use of benefits and costs of pollution abatement for two different integrated assessment models, the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model developed by Richard Tol, and the MITs Emissions Prediction and Policy Analysis (EPPA) model developed at MIT.

By demanding that environmental goods are evaluated equally in non-OECD (or poor) and OECD (or rich) countries and using equity weights, a relation between the elasticity of marginal utility e and the inequality aversion parameter γ is set up. The relation helps us to contract the intervals of e for a particular values of γ. Furthermore, it supports us to tighten the variation of optimal abatement levels when global social welfare is maximized.

We find out that the abatement targets of Kyoto protocol assume only a peculiar value for elasticity of marginal utility e for any possible given value of γ. This peculiar value of e produces no abatement levels for developing countries which is not an optimal target. From the other side, the abatement levels for developed countries are correctly assigned. On the opposite the Former Soviet Union has to play a central role among developing countries which is not foreseen in Kyoto protocol. Regions like Canada, Australia, China, India and East European Countries are changing their optimal abatement levels in a wide range which indicates that it is difficult to assign an abatement target to those countries.

Possible extension of my research concerning paper one to five, are the incorporation of repeated game theory, political commitment to cooperation and technology transfers, while concerning paper six, is the implementation of dynamic framework for a longer time interval, or again finding a way of including of political factors in modeling approach.

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