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 et al., 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

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

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heterogeneity of the countries involved (Chander and Tulkens, 1997, 2006; Eyckmans and 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 and Carraro, 2001; Osmani and Tol, 2005; Finus et al., 2006; Rubio and 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 and 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 and Sartzetakis (2002) and by Eyckmans (2003). Diamantoudi and 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).

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].

[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.

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 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 primary 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, in 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 poorly represented 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 and Goldewijk, 1994). The period 1990-2000 is based on observations of the World Resources Databases (WRI, 2001). 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, 2001). 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.

[2]For an introduction of D'Aspremont stability please refer to Barrett (1994).

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 surface 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 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 (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 (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 (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 (Fankhauser, 1994). The wetland value is assumed to have a 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 (Tol, 2002b). Impacts of climate change on energy consumption, agriculture, and cardio-

vascular 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 (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 (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) (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 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

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:

$$C_i = \alpha_i R_i^2 Y_i \tag{1}$$

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:

$$B_i = \beta_i \sum_j^n R_j E_j \tag{2}$$

where B denotes benefit, β the marginal damage costs of carbon dioxide emissions and E unabated emissions. Table (1) gives the parameters of Equations (1) and (2) as estimated by FUND. Moreover, the profit π_i of a country i is given as:

$$\pi_i = B_i - C_i = \beta_i \sum_j^n R_j E_j - \alpha_i R_i^2 Y_i \tag{3}$$

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:

$$d\pi_i/dR_i = \beta_i E_i - 2\alpha_i R_i Y_i = 0 \Rightarrow R_i = \beta_i E_i/(2\alpha_i Y_i) \tag{4}$$

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

$$d\pi_{i+j}/dR_i = 0 \Rightarrow E_i(\beta_i + \beta_j) - 2\alpha_i R_i Y_i = 0 \Rightarrow R_i = (\beta_i + \beta_j)E_i/(2\alpha_i Y_i) \tag{5}$$

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 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 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 3). 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 $\upsilon(C)$ (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:*
$\upsilon(C) : C \to \Re$,
$\upsilon(C) = max(\sum_1^c \pi_i) \quad i \in C, \quad C \subset N_{16}, \quad c \leq 16.$

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* $C_2 \subset N_{16}$:
$\upsilon(C_1 \cup C_2) > \upsilon(C_1) + \upsilon(C_2)$ *where* $C_1 \cap C_2 = \emptyset$.

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:*
$\forall k \notin C_1 \cup C_2 \quad \pi_k(C_1 \cup C_2) > \pi_k(C_1) \wedge \pi_k(C_1 \cup C_2) > \pi_k(C_2)$

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.

3.1 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 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 (see Observations 3.3 and 3.4.). 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 definitions of *inducement process, credible objection, and farsighted stability* are presented below:

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

- *there exists a finite 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 $C_k \cap C_l \neq \emptyset \wedge C_k \neq C_l \;\forall k, l \in [1, .., n]$*

  or

- *there exists a finite 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 $C_1 \supset C_2 \supset .. \supset C_{n-1} \supset C_n$*

$\pi_n(i)$, $\pi_m(i)$, $\pi_1(i)$ *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 3.7 *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 $\pi_n(i) \geq \pi_1(i) \quad \forall i \in G_1$*
- *there is no coalition induced from 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 3.8 *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 3.6 makes clear that there are two main types of inducement process. In the first type, there is a finite sequence of coalitions where *the countries in the final coalition* do not decrease their profits. In the second type, there is a finite 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 3.3 and 3.4, which help to 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 3.9 *An external inducement for coalition C_1 is possible if and only if:*

- *exists a finite 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 3.10 *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 3.11 *An internal inducement for coalition C_1 is possible if and only if:*

[3]Observations 3.3 and 3.4 make clear that this is sufficient to find all farsightedly stable coalitions.
[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).

- *there exists a finite 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 3.12 *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 3.13 *A sub-coalition inducement for coalition* C_k *is possible if and only if:*

- *exists a finite sequence of coalitions* $C_1, C_2 .. C_{m-1}, C_m$ *such as* $C_k \cap C_l \neq \emptyset \wedge C_k \neq C_l \ \forall\, k, l \in [1, .., m]$

- $\forall\, i \in C_m \quad \pi_m(i) \geq \pi_1(i)$

$\pi_1(i)$, $\pi_m(i)$ *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 3.14 *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 3.15 *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*
- *if the final coalition, which contains* $\boldsymbol{m}$ *members, is profitable, and the majority of* $\boldsymbol{n}$ *coalition-members increase their profits, but* $\boldsymbol{(m - n)}$ *of coalition-members decrease their profits then, the* $\boldsymbol{(m - n)}$ *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

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

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 and 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 3.1 *Definition 3.15 and definition 3.8 are equivalent* ***within our model assumptions*** *1, 2, 3 and 4.*

Proof: Definition 3.7 makes clear that:

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

So definition 3.15 and definition 3.8 both require that all possible coalitions that can be induced

[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.

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):

- $C_1 \subset C_n$ 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 3.16,* 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 (5) and Table (6) in Appendix 7 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 if there is a non-profitable farsightedly stable coalition, it can be found by starting from profitable coalitions and considering all possible inducement processes.

Observation 3.2 *If a non-profitable coalition C_m is farsighted stable if:*

1. *$\exists$ $C_1 \subset C_m$, and C_1 is profitable.*

Proof:

If a non-profitable coalition C_m is farsightedly stable then, there is a profitable sub-coalition $C_1 \subset C_m$, and there exists an inducement process from coalition C_1 to C_m and moreover, there is no credible objection against C_m.
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:

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

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_m must have a profitable sub-coalition in order to have a chance of being FS, which completes the first part of the proof.

Observation 3.3 *If a non-profitable coalition C_m is farsighted stable if and only if:*

1. *$\exists\ C_2 \mid C_2 \cap C_m \neq \emptyset$ where C_2 is profitable, and there exists an inducement process from coalition C_2 to C_m and there is no credible objection against C_m.*

The Proof, Second statement:

First direction: Let suppose that we have the inducement process, where C_m is a non-profitable farsightedly stable coalition:

$$a_{Atom_{structure}} \rightarrow C_1,\ \dots, C_{m-1} \rightarrow C_m \tag{6}$$

We try to find the inducement process where the countries in the final coalition increase their profit. As a consequence a non-profitable coalition can be induced from the atom structure. It implies that in the chain of the inducement process (6) $\exists\ C_i$ which is profitable $i \in N, 1 \leq i \leq m$.
Second Direction: The proof of second direction is again similar to the first direction, so we omit it.

Corollary 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 3.2.

Observation 3.4 *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.

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[9]. $\mathbf{Coal_{fs}}$ 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 3.16 *A set S is the Dynamic Large Consistent Set if and only if:*

[9]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.

- $\forall$ *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 3.5 *The set of all farsightedly stable coalitions* $\boldsymbol{Coal_{fs}}$ *is the Dynamic Large Consistent Set.*

Proof: Observations 3.3, 3.4 and Corollary 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[10]. 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

[10]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 3.3, 3.4 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.

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

$$\forall \; country \; i \in C_m \quad \exists \; C_{k_i} \quad | \pi_{C_{k_i}}(i) > \pi_{C_m}(i)$$

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

A coalition C_m is dominated if there are farsightedly stable coalitions where every country member of C_m gets higher profit.

Definition 4.2 *A coalition C_m dominates C_n, $C_m \succ C_n$ if and only if:*

$$\forall \; country \; i \in C_m \cap C_n \quad \pi_{C_m}(i) > \pi_{C_n}(i)$$

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

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

Definition 4.3 *A country i prefers C_m over C_n, $C_m \succ_i C_n$ if and only if:*

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

$\pi_{C_m}(i)$, $\pi_{C_n}(i)$ *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 4.4 *A coalition C_m is preferred over C_n, $C_m \succeq C_n$ if and only if:*

$$for \; the \; majority \; of \; country \; i \in C_m \cap C_n \; \pi_{C_m}(i) > \pi_{C_n}(i)$$

$\pi_{C_m}(i)$, $\pi_{C_n}(i)$ *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 (4.2) and (4.4) 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: 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) 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. [11].
The preferred four-member coalitions are (4–8) $(CAN, EEU, CAM, SAS)^{fs}$ and (4–6) $(USA, SEA, CHI, SSA)^{f}$ (see Table (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) $(CAN, EEU, CAM, SAS, SI$ and (5–5) $(USA, SEA, CHI, NAF, SSA)^{fs}$. Table (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 $(5-7)$.

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

Table 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 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:

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

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.

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 (1)[12]. The greater profit improvements are taking place in non-signatories[13] (as expected). The fraction of abatement change of each country when the six member coalition is formed, is shown in Figure (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 (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 (11). Figure (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 (12).
Thus farsighted stability produces better results in terms of welfare and abatement levels compare to D'Aspremont stability[14].

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

[12]Please note that the Figures (9), (10), (11), (12) are in Appendix 9.
[13]The countries that do not take part in any coalition are called non-signatories.
[14]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 $(CAN, JPK, EEU, CAM, LAM, NAF, SIS)$.

that our coalitions are farsightedly stable[15]. 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:

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

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

In Figures (5) and (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 (7)and Figure (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 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 (7)and Figure (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 and Tol, 2005; **?**) 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[16].

Farsighted stable coalitions generate better results in terms of welfare and abatement levels compare to D'Aspremont stable coalitions[17].

[15] 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.

[16] 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.

[17] 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.

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.

Acknowledgment

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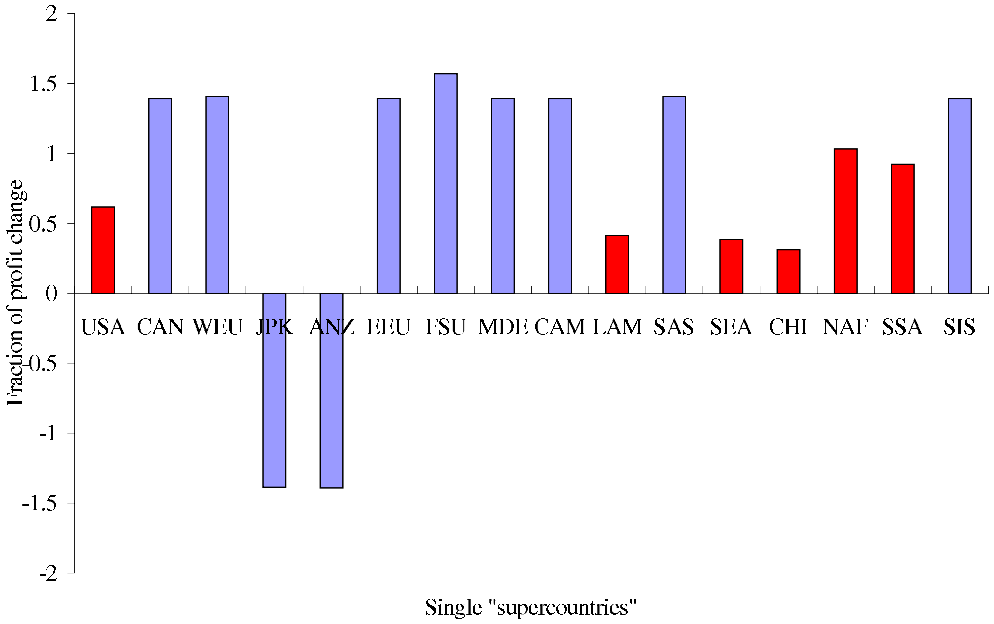

Figure 1: Fraction of profit change when the first coalition is formed, red color → first coalition, violet color → nonsignatories

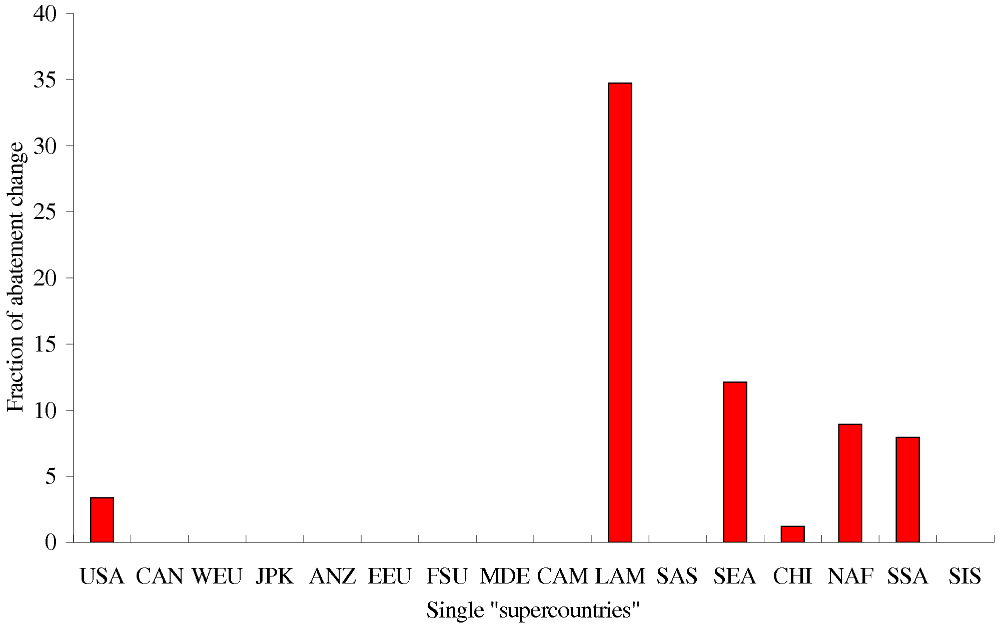

Figure 2: Fraction of abatement change when the first coalition is formed, red color → first coalition

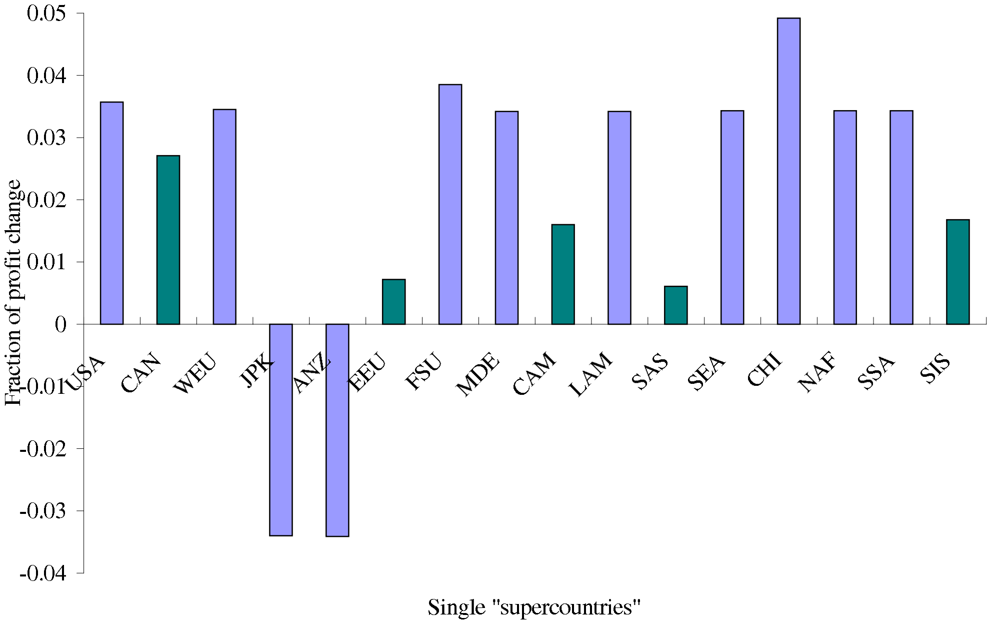

Figure 3: Fraction of profit change when the second coalition is formed, green color → second coalition, violet color → nonsignatories

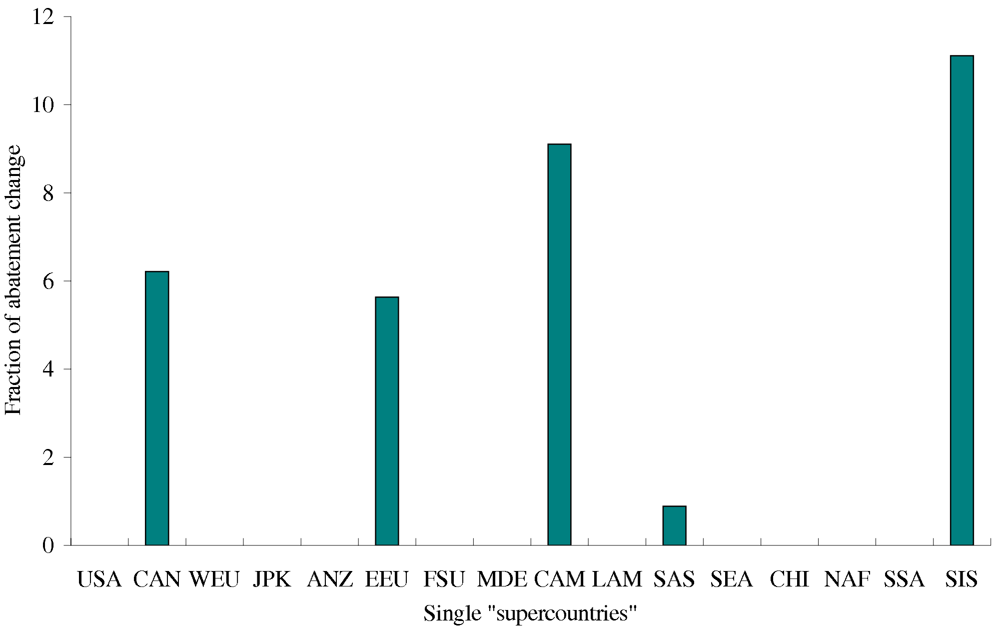

Figure 4: Fraction of abatement change when the second coalition is formed, green color → second coalition

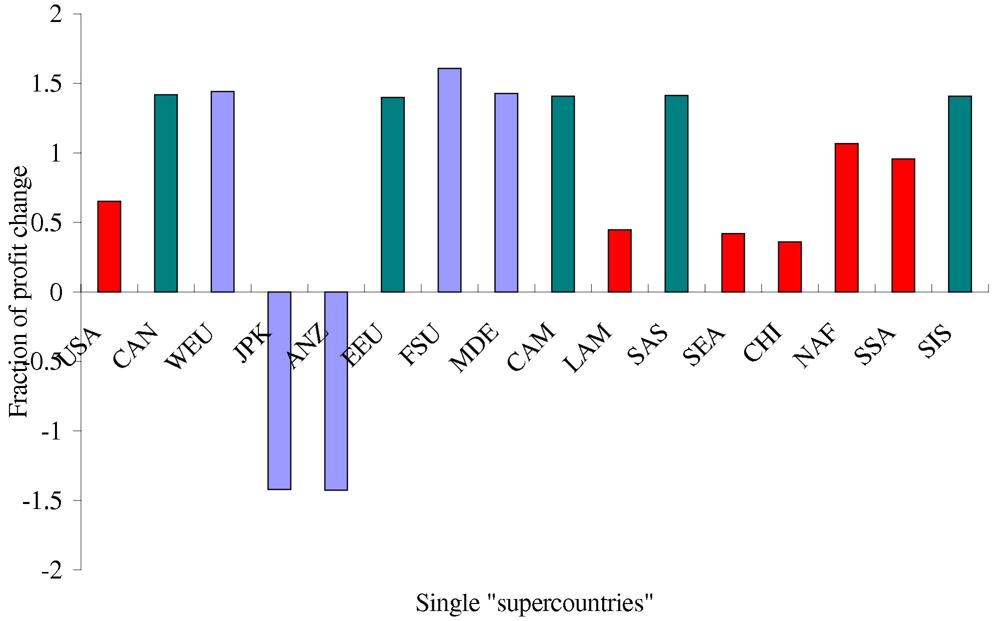

Figure 5: Fraction of profit change when both coalitions are formed, red color → first coalition, green color → second coalition, violet color → nonsignatories

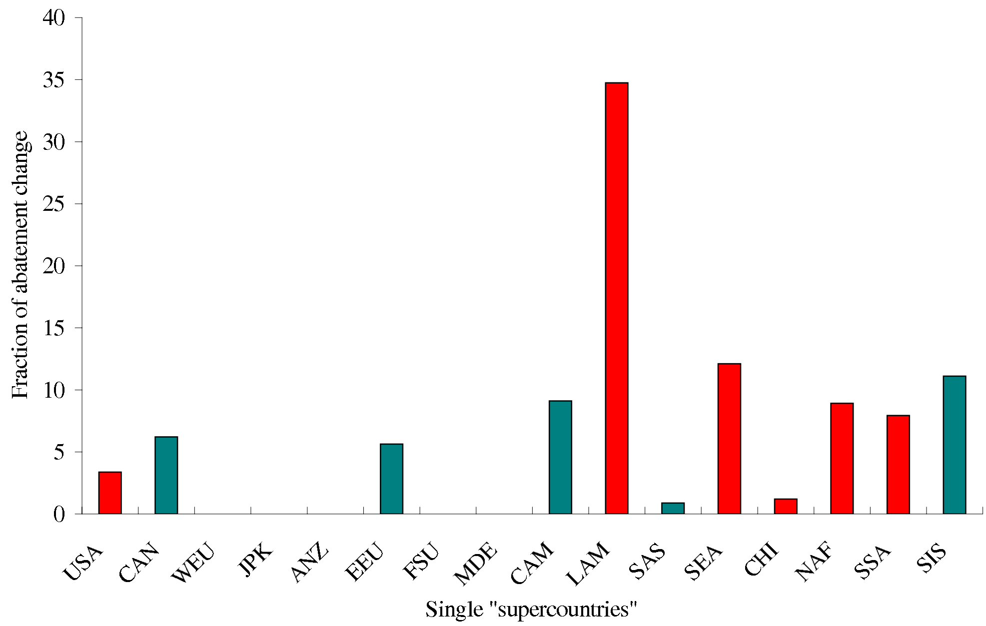

Figure 6: Fraction of abatement change when both coalitions are formed, red color → first coalition, green color → second coalition

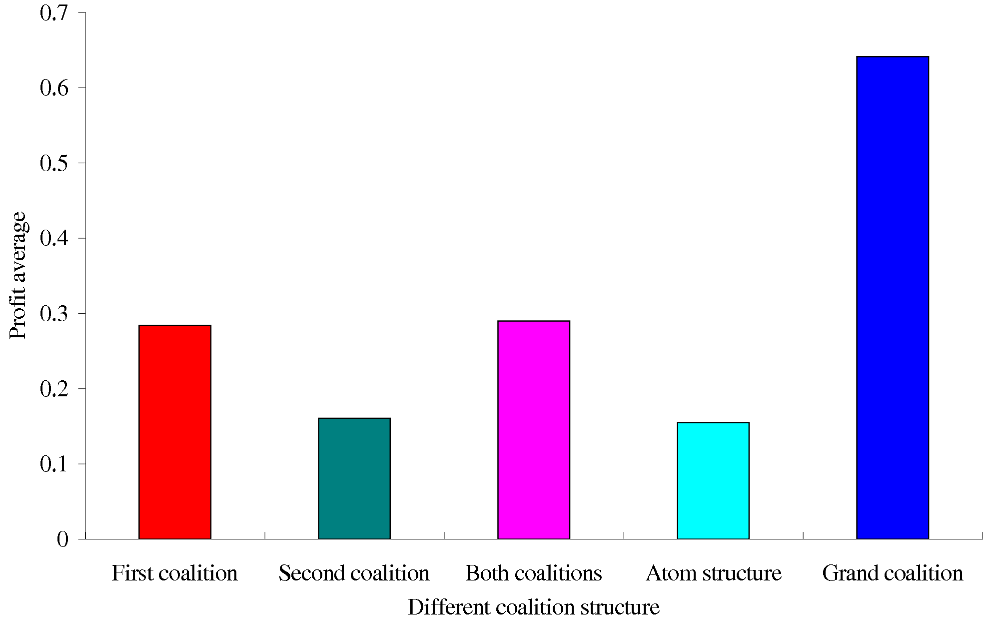

Figure 7: Average profit levels of different coalition structure

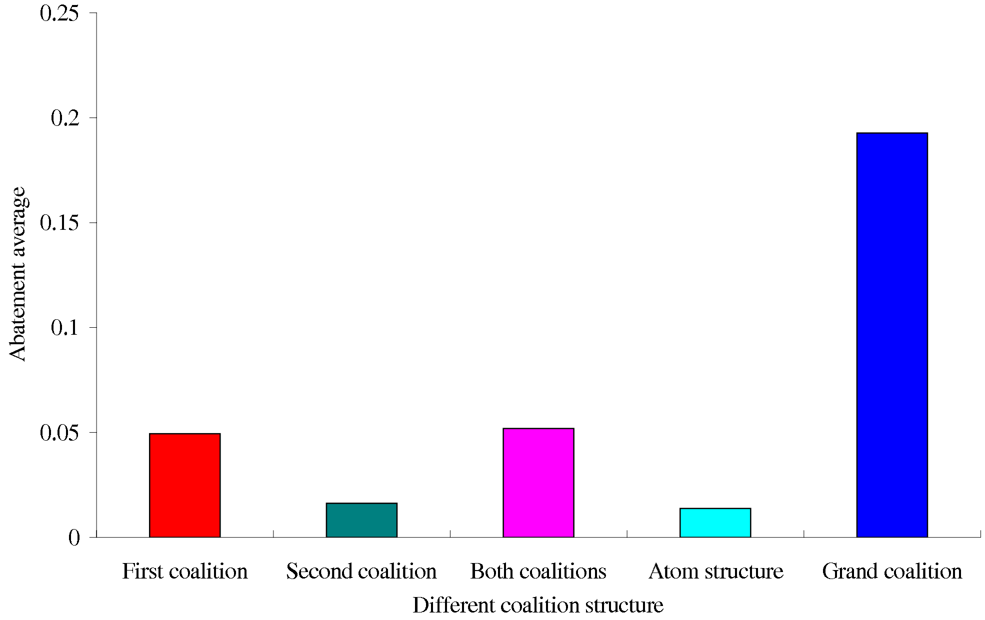

Figure 8: Average abatement levels of different coalition structure

7 Appendix

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 (5). It tests a coalition *for external farsighted stability* (EFS, see definition (3.10)). Suppose we would like to check coalition $C_n \equiv (1, 2 \dots n)$ for EFS.

Table 5: Algorithm for finding externally farsightedly stable (EFS) coalitions

```
Take the coalition C_n ≡ (1, 2 ... n) where n < 16.
Calculate π_1(1)...π_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 ≥ (n + 1) where n elements are always (1, 2 ... n).
take a coalition with i countries
Calculate π_2(1)...π_2(16), the profit of this coalition structure.
if    [π_2(1) > π_1(1) ∧ π_2(2) > π_1(2) ∧ ... ∧ π_2(i) > π_1(i)] (main condition)
the coalition (1, 2 ... 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 ... n) is externally farsightedly stable.
```

If the algorithm of Table (5) finds a $\boldsymbol{i}$ member-coalition C_i for which *the main condition* $[\pi_2(1) > \pi_1(1) \wedge \pi_2(2) > \pi_1(2) \wedge \dots \wedge \pi_2(i-1) > \pi_1(i-1) \wedge \pi_2(i) > \pi_1(i)]$ 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 $C_n \equiv (1, 2 \dots n)$. 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 (6).

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

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

Table 6: Algorithm for finding internally farsightedly stable (EFS) coalitions

```
Take the coalition C_n ≡ (1, 2 ... n) where n ≤ 16.
Calculate π(1)..π(i1)..π(i5)..π(16) the profits of this coalition structure.
for i=2 to (n-1) (find all sub-coalition with i elements from coalition (1, 2 ... n))
Take a sub-coalition with i elements.
Calculate π'(1)..π'(i1)..π'(i5)..π'(16) the profits of this coalition structure.
if    [π'(1) > π(1) ∧ π'(2) > π(2) ∧ π'(i − 1) > π(i − 1) ∧ π'(i) > π(i)] (main condition)
the coalition (1, 2 ... 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 ... n) is internally farsightedly stable.
```

coalitions are internally farsightedly stable (including the three-member coalitions). Three-member coalitions which are not externally farsightedly stable are presented in Tables 7, 8 and 9. The first column of Table 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 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 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 7 are similar to columns one, two and three,and Tables 8 and 9 are similar to Table 7. Tables 10 and 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 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 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 11 is similar to Table 10.

Table 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 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 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 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 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

8 Appendix

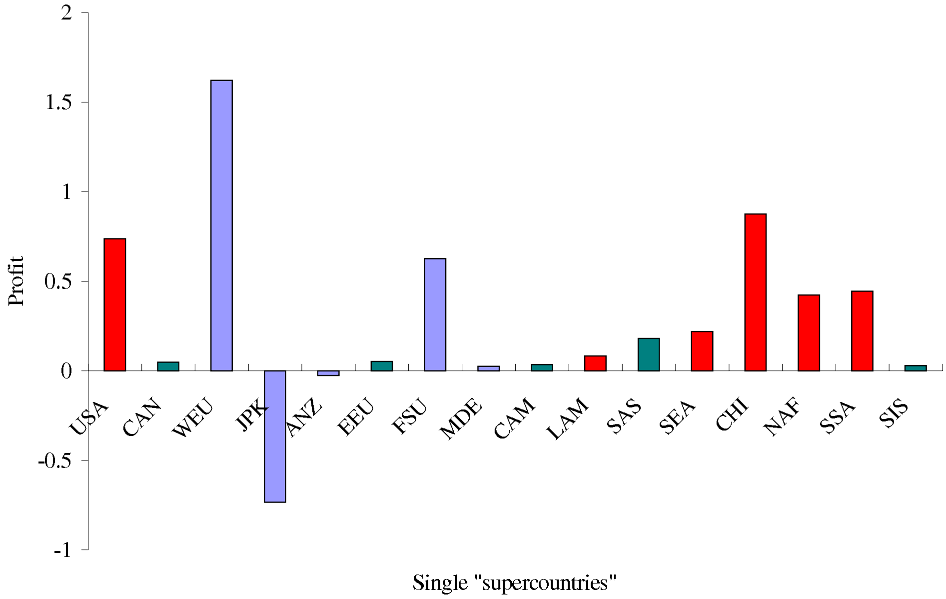

Figure 9: Profit levels when both coalitions are formed, red color → first coalition, green color → second coalition, violet color → nonsignatories

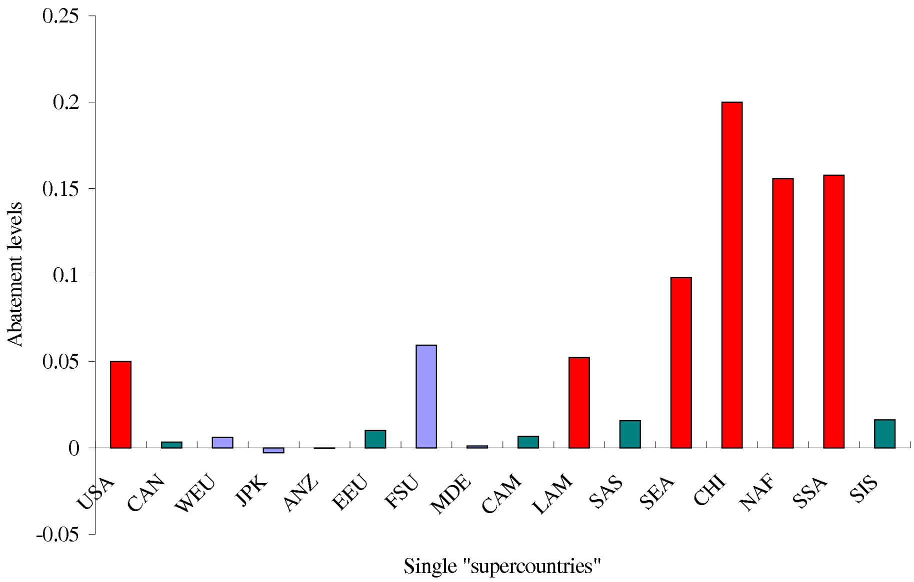

Figure 10: Abatement levels when both coalitions are formed, red color → first coalition, green color → second coalition, violet color → nonsignatories

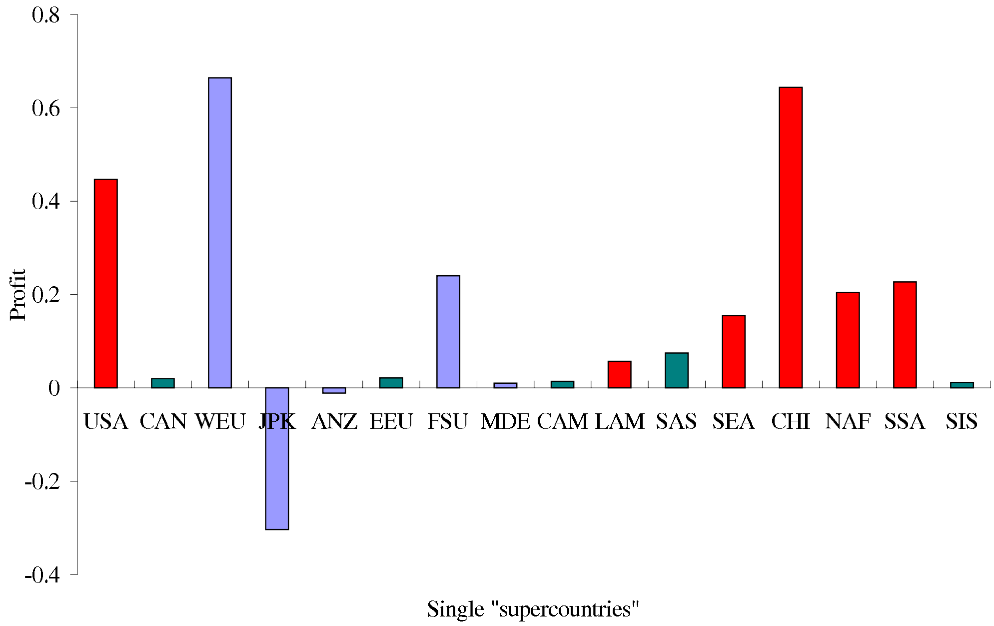

Figure 11: Profit levels in atom structure, red color → first coalition, green color → second coalition, violet color → nonsignatories

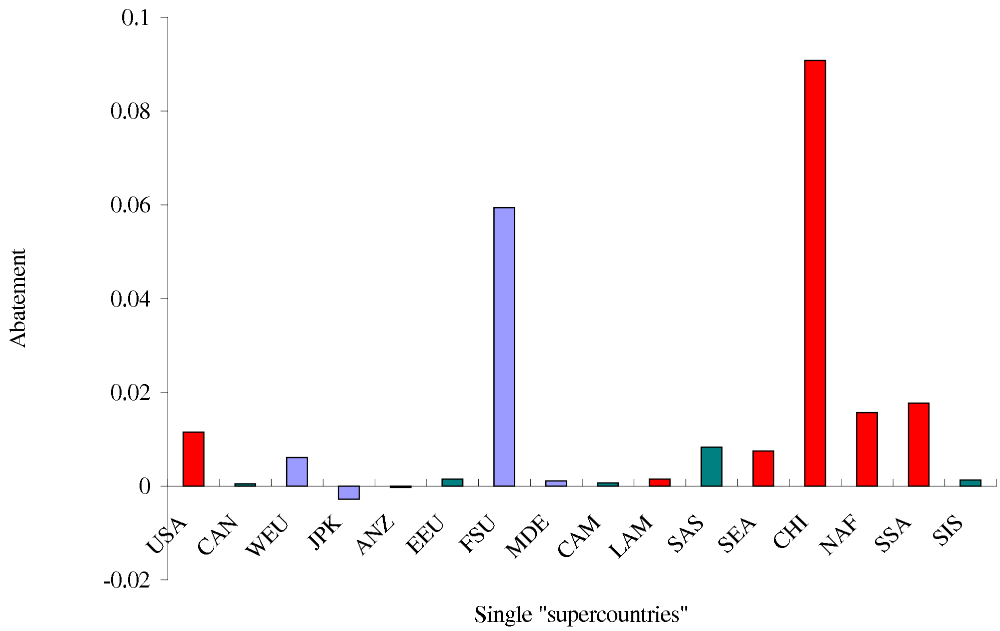

Figure 12: Abatement levels in atom structure, red color → first coalition, green color → second coalition, violet color → nonsignatories

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