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

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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 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

[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.

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.

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 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

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

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.

3.1 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.*

[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).

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:

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 $C_1, C_2 \ldots C_{n-1}, C_n$*
  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

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

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).*

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):

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

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

[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).

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

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

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

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.

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 coalition as well as non-members of coalition (the country that does not belong to coalition) remain non-members.

Definition 4.1 *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 coalition* S *and coalition* $S - \{i\}$ *is formed.*

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

Definition 4.2 *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 coalition* $S + \{j\}$
$\pi(j)_{j \notin S}$ *is profit of a country* j *when 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* 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 4.3 *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),
$(CAN, JPK, LAM, SAS, SSA)$,
$(CAN, JPK, EEU, CAM, LAM, NAF, SIS)$.

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

[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).

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

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

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

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

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)

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.

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).

7.1 Conceptual discussion

We claim that 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 the 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 D'Aspremont stable coalitions. There is no free-riding initiative as coalition is internal D'Aspremont stable. This signifies that

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

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:

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

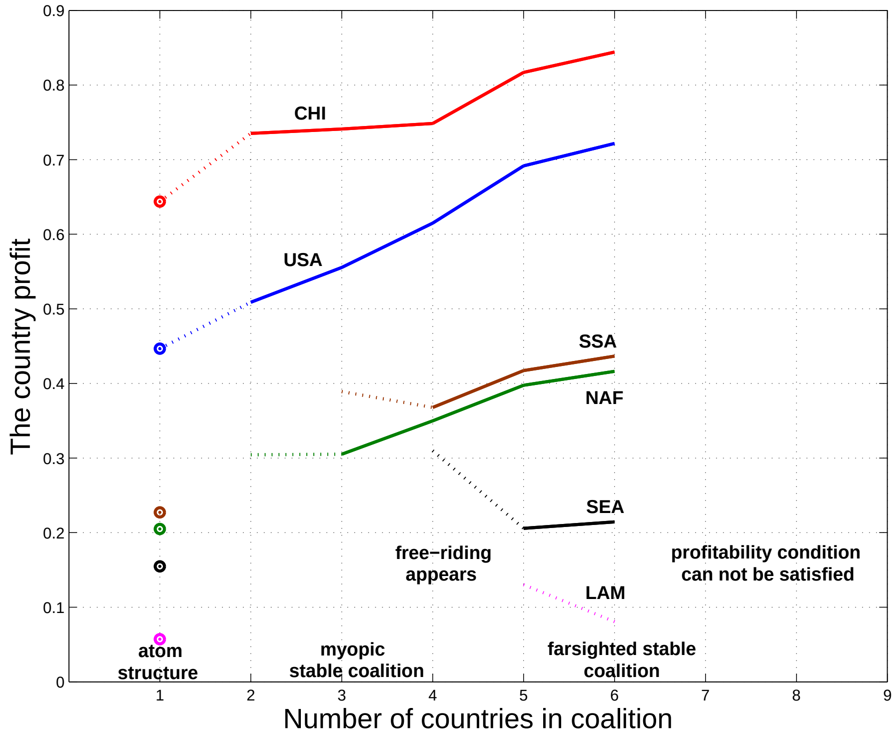

Figure 1: The comparison between the D'Aspremont and farsighted stability

But this is better seen at Fig (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. 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 function of profitability condition* which is hard to be satisfied 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 (1). We focus on 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 member which has a negative marginal damage cost of carbon dioxide emissions β, see Table (1)).

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].

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.
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

[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).

(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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