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Simulating a Sequential Coalition Formation Process for the Climate Change Problem: First Come, but Second Served?

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Simulating a Sequential Coalition Formation Process for the Climate Change Problem: First Come, but Second Served?

by

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Abstract

We analyze stability of self-enforcing climate agreements based on a data set generated by the CLIMNEG world simulation model (CWSM), version 1.2. We consider two new aspects which appear important in actual treaty-making. First, we consider a sequential coalition formation process where players can make proposals which are either accepted or countered by other proposals. Second, we analyze whether a moderator, like an international organization, even without enforcement power, can improve upon globally suboptimal outcomes through coordinating actions by making recommendations that must be Pareto-improving to all parties. We discuss the conceptual difficulties of implementing our algorithm.

Keywords: International Climate Agreements, Sequential Coalition Formation, Coordination through Moderator, Integrated Assessment Model, Algorithm for Computations

JEL-Classification: C79, H87, Q54

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1. Introduction

Cooperation in transboundary pollution has proved, and still proves, difficult. Despite cooperation among nations could raise global welfare because of multilateral negative externalities, and could benefit all nations if accompanied by fair sharing arrangements, strong free-rider incentives prevail. Curbing greenhouse gases illustrates the problems of cooperation vividly. International response to global warming is often traced back to 1988 when the Intergovernmental Panel on Climate Change (IPCC) was founded – an international body initiated by the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) that gathers and summarizes current world-wide scientific evidence on climate change. In 1992, at the Earth Summit held in Rio de Janeiro, the United Nations Framework Convention on Climate Change (UNFCCC) was established with the aim to promote international action to stabilise greenhouse gas (GHG) concentrations in the atmosphere, at levels that "avoid dangerous anthropogenic climate change". However, it was not until 1997 when 38 countries agreed to specific emission ceilings under the Kyoto Protocol to be met in the "commitment period" 2008-2012. Again, it was not before 2002 when this treaty was ratified. This did not happen before several concessions had been granted to various participants and after the USA had declared to withdraw from the treaty.

Currently, in the light of the Stern report (Stern 2006) and the most recent IPCC report (IPCC 2007), a follow-up "Post-Kyoto" agreement is being negotiated that should set emission ceilings for the period after 2012. The aim is to reduce emissions further and to encourage participation of the major polluter USA, as well as the new emerging polluters China and India.

Parallel to this political development, the interest in economics to analyze the reasons and possible remedies for the problem of international environmental cooperation emerged. One strand of literature focused on the game theoretic analysis of international environmental agreements (IEAs) which can be traced back to Barrett (1994), Chander and Tulkens (1992), Carraro and Siniscalco (1993) and Hoel (1991). Later papers focused on various designs and measures that could mitigate the free-rider problem. Due to the many papers, we refer the reader to the surveys by Barrett (2003) and Finus (2003, 2008). Other contributions departed from the assumption of a static payoff structure of the initial papers and captured the dynamic nature of the stock pollutants "greenhouse gases". This is also the starting point of the second strand of literature that ignored coalition formation but modeled optimal policy responses in integrated assessment models that capture the dynamic interaction between the economy and the environment and which was pioneered by Nordhaus (1994). This initiated many other papers which are surveyed for instance in Böhringer and Löschel (2006). Naturally, there have also been attempts to combine both strands as for instance Bosello et al. (2003), Eyckmans and Tulkens (2003), Eyckmans and Finus (2006) and Weikard et al. (2006). On the one hand, this adds more realism to the analysis; on the other hand, this is the only way to derive results in richer game theoretic frameworks where analytical solutions are impossible to obtain.

This paper is in the tradition of a combined approach: it links a game theoretic module of coalition formation to an integrated assessment numerical simulation module. The empirical module is based on the CLIMNEG World Simulation Model (CWSM) as for instance used in Eyckmans and Tulkens (2003), Eyckmans and Finus (2006), though we use the updated version 1.2. Different from these papers but also different from many theoretical contributions on the formation and stability of IEAs, our game theoretic module looks at two new aspects.

First, we do not model coalition formation as a simultaneous but as a sequential decision process. This is motivated by the observation that usually some countries take the initiative of forming IEAs. Others join later or decide not to follow suit. The evolvement of membership in international agreements is a typical feature of many IEAs and is reported for instance in Finus (2003) for many environmental treaties.

Second, despite we follow the mainstream of the literature, assuming that there is no global authority that can enforce cooperation, we consider the possibility of a third party which aims at coordinating actions, thereby improving upon the disappointing record of cooperation. The analysis of a moderator, as we call it, is based on two arguments. The first argument takes a positive view. There are many international organizations that directly or indirectly influence the outcome of negotiations. For instance, the IPCC provides scientific evidence on climate change of which the most important in our context is evidence on damages caused by climate change and the costs associated with curbing greenhouse gases. Also the United Nations, in particular the Environmental Programme (UNEP) advices parties and tries to spur action. The World Bank administers some of the climate funds that have been set up to provide incentive of participation for developing and least developed countries. It also plays an active role to oversee the Clean Development Mechanism, one of the flexible instruments under the Kyoto Protocol to keep abatement costs down. The second argument takes a normative view. It simply asks if and how a moderator can improve upon the efforts of cooperation through coordinating actions among nations.

With respect to both aspects this paper takes first steps, hoping to initiate more research. As we spell out in more detail in subsequent sections, both aspects pose many conceptual problems that require more research. It appears to us that the closest connections to recent research are the papers by Germain et al. (2003), Rubio and Ulph (2007), Ulph (2004) and De Zeeuw (2007). We view coalition formation as a two-stage game. In the first stage players decide upon membership and in the second stage they decide upon their economic strategies, which are abatement strategies and in richer models also investment in capital and research. The game is solved backward: equilibrium economic strategies determine the payoff of players and are the basis to decide upon membership. Stability of membership is analyzed along the entire time path. In Germain et al. (2003) this is done in the tradition of cooperative games by invoking the concept of core stability for the membership game. In Rubio and Ulph (2007) and Ulph (2004) this is analyzed by invoking the concept of internal and external stability with a stronger flavor of non-cooperative game theory. All of these papers ignore the role of a coordinator and assume a simultaneous decision about membership at each time t. Moreover, Rubio and Ulph (2007) and Ulph (2004) assume symmetric players for analytical tractability. In contrast, we consider heterogeneous players, a sequential membership game, the role of a moderator, though in a simplistic way, but assume that membership decisions are based on discounted payoffs of a differential climate game. This limitation already suggests an avenue for future research, which we spell out in more detail in the last section of this paper. Nevertheless, we believe that our paper is an important step for the further development of modeling the negotiation and formation process of cooperative arrangements in international pollution control.

2. Overview of the Model

Following Bloch (2003), we view the coalition formation process as a two-stage game. In the first stage, players, $i \in I = \{1,...,n\}$, which are world regions in our empirical context, decide upon their membership in coalitions, which are climate agreements in our context. This stage is modeled along the lines of the sequential move unanimity game (SMUG) proposed by Bloch (1995). In this game, an initiator proposes a coalition. Prospective members of this coalition are sequentially asked for acceptance. If all potential members accept, the coalition is formed. If the proposed coalition is not the grand coalition, a new initiator among the remaining players can make a new proposal. If a player rejects a proposal, he can make a new proposal. The formation process continues until all players have agreed to be either a member of a (non-trivial) coalition or decided to remain a singleton.[1] The first stage of the game is described in more detail in section 4. The decision process in the first stage leads to some coalition structure $c = \{c_1,...,c_m\}$

[1] A non-trivial coalition is a coalition with at least two members.

where $c \in C$ is a partition of players in disjoint non-empty sets, $c_k \cap c_\ell = \emptyset \ \forall \ k \neq \ell$ and $\bigcup_\ell c_\ell = I$.[2]

In the second stage, players choose their economic strategies, which are abatement and investment strategies in the CLIMNEG world simulation model (CWSM), version 1.2, based on the economic implications as predicted by this model. For a given coalition structure c, this implies a payoff vector $v(c) = (v_1(c),...., v_n(c))$. That is, a coalition structure $c \in C$ is mapped into a vector of individual payoffs $v(c) \in V(C)$ called valuations. In case a transfer scheme is implemented, this leads to "modified valuations" $v_i^T(c) = v_i(c) + \Psi_i$ where $\Psi_i > 0$ implies to receive a transfer and $\Psi_i < 0$ to pay a transfer with the understanding that transfers are only paid among coalition members and that transfers balance, i.e. $\sum_{i \in c_\ell} \Psi_i = 0 \ \forall \ c_l \in c$.

The entire game is solved by backward induction. For the second stage, we follow the standard assumption in the literature on coalition formation and solve for the *coalitional Nash equilibrium* in economic strategies.[3] That is, members of coalition c_ℓ in coalition structure c choose their economic strategies such as to maximize the aggregate payoff to their coalition, taking the strategies of outsiders as given. In CWSM this payoff is the net present value of a payoff stream, accounting for the fact that climate change is a stock pollution problem. The details of the second stage are described in section 3.

For the first stage, which consists of many sub-stages due to the sequential coalition formation process, we solve for the subgame-perfect equilibrium in membership strategies. That is, each player, either in the role of an initiator or in the role of a player who is asked for acceptance

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2 For instance, in the case of three players, C comprises five different coalition structures: $c^1 = \{\{1\},\{2\},\{3\}\}$, $c^2 = \{\{1,2\},\{3\}\}$, $c^3 = \{\{1,3\},\{2\}\}$, $c^4 = \{\{1\},\{2,3\}\}$ and $c^5 = \{\{1,2,3\}\}$.

3 For a summary of this literature in the general context, see Bloch (2003) and in the context of IEAs, see Finus (2003). Sometimes a coalitional Nash equilibrium is also called a coalitional equilibrium (Ichiishi 1981) or a partial Nash equilibrium between coalitions (Chander and Tulkens 1997).

should choose her best reply at each point in time for the rest of the game, given the strategies of the other players. The details of the first stage are explained in section 4.

3. Second Stage of Coalition Formation

3.1 Data and Computations

The CWSM is an integrated assessment, economy-climate model capturing the endogenous feedback of climate change damages on production and consumption. As the seminal RICE model by Nordhaus and Yang (1996), CWSM is a dynamic, long-term, perfect foresight, Ramsey-type optimal growth model with a global climate externality. Since an extensive exposition of the model, including the procedure of computing valuations, is provided in Eyckmans and Tulkens (2003) and Eyckmans and Finus (2006 and 2009), we describe here only its main features. A brief description of the main equations and parameters is provided in Appendix 1.

In CWSM, the world is divided into six regions: *USA*, *JPN* (Japan), *EU* (European Union), *CHN* (China), *FSU* (Former Soviet Union) and *ROW* (Rest of the World). In every region, and in every time period, output is allocated to consumption, investment, emission abatement expenditures and climate change damages. Output is modeled as a Cobb-Douglas production function with capital and labor input. Capital is built up through investment and depreciates at a fixed rate. Labour supply is assumed to be inelastic. Therefore, investment is the only endogenous production input and constitutes the first choice variable in the model. Abatement expenditures are expressed as output losses and are a function of relative emission reduction compared to the business-as-usual (BAU) scenario without any abatement policy. Climate change damages are also expressed as output losses and are a function of temperature change compared to pre-industrial times. Temperature change depends on the stock of greenhouse gases, which in turn depends on emissions that accumulate in the atmosphere. Finally, emissions are proportional to production, but can be reduced by abatement activities. The rate of emission abatement compared to the BAU scenario constitutes the second choice variable in this model.

Both choice variables (investment and abatement) affect output, abatement costs, damage costs and therefore also consumption domestically but also abroad. With respect to abatement this is obvious since remaining emissions (after abatement) increases the stock of greenhouse gases, which affects environmental damages in every country. However, this is also true for investment since capital is an input in the production process and emissions are proportional to production. Technological progress is captured in the CWSM in an exogenous fashion. It increases the production potential and decreases the emission-output ratio (i.e. increases energy effiency) over time. Finally, welfare is measured as total lifetime discounted consumption.

An economic strategy vector is denoted by $s^*(c)$ and consists in CWSM of a time path of 35 decades for emission abatement and investment for all six regions, hence its length is 2 x 35 x 6 = 420. Valuations without transfers $v(c)=(v_1(c),...,v_n(c))$ for coalition structure $c \in C$ are defined as $v_i(c):=W_i(s^*(c))$ where $s^*(c)$ is the coalitional Nash equilibrium economic strategy vector which is defined as:

(1) $$\forall c_\ell \in c: \sum_{i\in c_\ell} W_i(s^*_{c_\ell}(c), s^*_{-s_\ell}(c)) \geq \sum_{i\in c_\ell} W_i(s_{c_\ell}(c), s^*_{-c_\ell}(s)) \qquad \forall s_{c_\ell}(c)$$

where $W_i(\ )$ is the discounted pyaoff of player i, $s_{c_\ell}(c)$ is the economic strategy vector of coalition c_ℓ, $s_{-c_\ell}(c)$ the vector of all other regions not belonging to c_ℓ and an asterisk denotes equilibrium strategies. Determing $s^*(c)$ for every coalition structure $c \in C$ (noting $v_i(c):=W_i(s^*(c))$), gives the set of valuations $V(C)$.

Computationally, the coalitional Nash equilibria are computed by means of a standard iterative algorithm assuming that all members of coalition $c_\ell \in c$ jointly maximize the aggregate payoff to their coalition $\sum_{i\in c_\ell} W_i(s)$ with respect to $s_{c_\ell}(c)$, while taking the strategies of outsiders $s_{-c_\ell}(c)$ as given. Repeating this optimization problem for each strategic player (coalition or singleton) and iterating until strategy vectors do not change more than some prespecified tolerance level, gives $s^*(c)$ which is substituted into W_i in order to derive $v(c)=(v_1(c),...,v_n(c))$. Since the CWSM comprises six regions, vector $v(c)$ has six entries. For each coalition structure, the equilibrium economic strategy has to be computed in order to derive the set of valuations V(C). Because six regions imply 203 different coalition structures, the set of valuations is a matrix of dimension 203x6. The set of coalition structures comprises the coalition structures with only singletons (no cooperation), the coalition structure with only one coalition, namely the grand coalition (full cooperation), 56 coalition structures with only one non-trivial coalition and some singletons (partial single cooperation), and 145 coalition structures with at least two non-trivial coalitions (partial multiple cooperation). Thus, the dimension of our set of valuations is larger than in Eyckmans and Tulkens (2003) because we also consider multiple coalition structures as in Eyckmans and Finus (2006).

Strategically, this means members that belong to the same coalition behave cooperatively towards their fellow members (otherwise cooperation would not be worthwhile analyzing), but non-cooperatively towards outsiders. *Economically*, this means strategies are group efficient within coalition c_ℓ but not globally efficient as long as the grand coalition does not form. It also means that the equilibrium economic strategy vector $s^*(c)$ corresponds to the classical "social or global optimum" if c is the coalition structure with the grand coalition, and corresponds to the classical "Nash equilibrium" if c is the coalition structure with only singletons. Hence, any inefficiency, i.e. global welfare loss of partial single or partial multiple cooperation compared to the global optimum stems from the fact that the grand coalition does not form (as this may not be an equilibrium coalition as analyzed in the first stage of coalition formation).

Valuations with transfers are defined as $v_i^T(c)=v_i(c)+\Psi_i$ where the transfer Ψ_i is paid ($\Psi_i<0$) or received ($\Psi_i>0$) in a lump-sum fashion (expressed in discounted consumption at time $t=0$) and hence does not affect equilibrium economic strategies in the CWSM as proved in

Eyckmans and Tulkens (2003). This implies a TU-framework and the transfer scheme proposed by these authors leads to valuations

$$(2) \qquad v_i^T(c) = v_i(c^N) + \lambda_i \left[\sum_{j \in c_\ell} (v_j(c) - v_j(c^N)) \right] \qquad \forall i \in c_\ell, \quad \forall c_\ell \in c.$$

That is, every region i in coalition $c_\ell \in c$ receives its payoff in the coalition structure with only singletons which is denoted by c^N (first term on the R.H.S. in (2); $c^N = \{\{1\},...,\{n\}\}$), and additionally a share $\lambda_i \geq 0$, $\sum_{i \in c_\ell} \lambda_i = 1$, from the total coalitional surplus of cooperation when moving from coalition structure c^N with no cooperation to some other coalition structure c (term in square brackets on the R.H.S. in (2)). Shares are those proposed by Eyckmans and Tulkens (2003) and reflect the relation between individual and global discounted marginal climate change damages in coalition structure c. Hence, the second term favors regions with relatively high marginal damages since they are entitled to a larger share of the surplus of their coalition. The motivation for this transfer scheme is twofold. First, it can be normatively argued that this transfer scheme embodies a standard notion of fairness: regions that are hurt more by climate change receive a higher share from the gains from cooperation. Second, already Chander and Tulkens (1997) but also Eyckmans and Tulkens (2003) have shown that this transfer rule gives rise to an allocation in the core in a global emission game, though we employ a different stability concept.

3.2 Properties of Valuations

Table 1 displays individual valuations, generated by CWSM, with and without transfers for a selection of coalition structures.[4] The last two columns display aggregate valuations at the World level in absolute and relative terms. The relative magnitudes can be interpreted as a "closing the

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[4] We do not display the ecological implications (i.e. total emissions and concentration) of different coalition structures in this paper. For version 1 of CWSM, this is for instance provided in Eyckmans and Finus (2006). The complete matrix of valuations is available upon request from the authors.

gap index" (abbreviated CGX), measuring how close a coalition structure comes to the global optimum where the performance in the grand coalition (full cooperation) is 100 percent and the performance in the coalition structure with only singletons (no cooperation) is 0 percent by definition (see the legend of Table 1).

Table 1 about here

Apart from stressing that both full and partial cooperation make a difference compared to no cooperation, Table 1 illustrates that not only the size of a coalition matters for the global success of cooperation, but also the identity of its members. Put differently, the commonly hold view that a high participation automatically indicates the success of an IEA may be wrong. For instance, coalition structure No. 152 including the five members USA, JPN, EU, CHN and FSU ranks lower than many coalition structures comprising smaller coalitions as for instance coalition structure No. 150 and No. 151.

As a general tendency, the importance of particular regions for global welfare decreases along the following sequence: ROW, CHN, USA, EU, FSU and JPN. ROW´s and CHN´s important role stems from the fact that they can provide cheap abatement. Similarly, JPN´s lesser importance is due to her steep marginal abatement cost curve. However, there is also an additional dimension related to environmental damages. Because optimal economic strategies are derived from coalitions maximizing the joint welfare of its members, the higher the marginal damages of coalition members are, the higher joint abatement efforts will be, everything else being equal. This has not only a positive spillover effect on fellow coalition members but also on outsiders. (See more on this below.) This explains the importance of EU for cooperation.

Table 1 is also useful to illustrate five properties of our two sets of valuations, with and without transfers, $V(C)$ and $V^T(C)$, respectively. These properties turn out to be useful when analyzing the incentives of coalition formation and stability in section 4.

The first property is called superadditivity (SAD) and means that the aggregate valuation of coalition c_k and coalition c_ℓ (that may be trivial or non-trivial coalitions) increases if they merge.

Property 1: Superadditivity

A coalition game is superadditive if and only if for all $c_k, c_\ell \in c$, $c_k \cup c_\ell \in \hat{c}$ *and* $c, \hat{c} \in C$:

$\sum_{i \in c_k \cup c_\ell} v_i(\hat{c}) \geq \sum_{i \in c_k} v_i(c) + \sum_{i \in c_\ell} v_i(c)$ *where* $\hat{c}$ *is derived from c by merging two coalitions in c.*

That is, there is "coalitional gain" from cooperation and hence cooperation is "group rational" or "coalitionally rational". Hence, SAD provides a general incentive for cooperation. For instance, in coalition structure No. 195 {{USA},{JPN, EU, FSU},{CHN},{ROW}}, the total payoff of USA, JPN, EU and FSU is 496,243.2 bln$ US whereas if they merge, leading to coalition structure No. 173 {{USA, JPN, EU, FSU},{CHN},{ROW}} the total payoff to these four players increases to 496,428.6 bln$ US.

The intuition behind this property, which has been put forward, is: "if two coalitions merge, they always have the option of behaving as they did when they were separate, and so their total payoff should not fall" (Maskin 2003, p. 9). However, this intuition might be false in our context. A sufficient condition for SAD to hold is to assume that if coalitions merge, outsiders' equilibrium economic strategies remain unchanged. In other words, there is no externality across coalitions. However, this assumption does not hold in the case of the CWSM. For instance, an enlargement of a coalition leads to a new coalitional equilibrium with higher total abatement of those players involved in this move but lower abatement of other players. In the climate context this has been called leakage-effect. Hence, the fact that SAD still holds in CWSM means that the leakage-effect is sufficiently small not to contradict the good intentions of the enlarged coalition.

The second property is called positive externality (PEX), meaning that the valuation of region j increases if coalition c_k and coalition c_ℓ merge where j is not involved in this merger (i.e. does neither belong to c_k nor to c_ℓ).

Property 2: Positive Externality

A coalition game exhibits a positive externality if and only if for all $c_k, c_\ell \in c$, $c_k \cup c_\ell \in \hat{c}$, $c, \hat{c} \in C$ *and* $i \notin c_k \cup c_\ell : v_i(\hat{c}) \geq v_i(c)$ *where* $\hat{c}$ *is derived from c by merging two coalitions in c.*

In contrast to SAD, which may be seen as a positive internal spillover to those players increasing the degree of cooperation (through the merger of coalitions), PEX implies a positive spillover to outsiders. Hence, PEX makes free-riding attractive and works in the opposite direction than SAD in terms of the incentives for cooperation.[5]

The driving force behind this property can be decomposed into two effects, which are closely related to our explanation above, why SAD could, in principle, fail to hold. First, global abatement will increase after the merger as the new coalition will increase abatement efforts. Although outsiders will respond to the coalition's increase of abatement by reducing their own abatement efforts, this response is less than proportional (i.e. incomplete leakage). The resulting net increase of global abatement is beneficial to all players because it reduces climate change damages. Second, outsiders to the merger incur lower abatement costs due to reduced abatement efforts.

The property PEX is evident for instance in Table 1 by comparing again coalition structures No. 195 and No. 173. In No. 195, the singleton players CHN and ROW receive a payoff of 299,267.3 bln$ US and 345,276 bln$ US, respectively, whereas in No. 173, after the USA has joined the coalition {JPN, EU, FSU}, their payoffs are given by 300,001.6 bln$ US and 346,569.3 bln$ US, respectively.

Table 1 also illustrates that PEX usually makes it most attractive from a single region´s point of view that all players cooperate, except the region itself, irrespective whether transfers are

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5 From the recent literature on coalition theory it appears that many economic problems either belong to positive or negative externality games for which some general results can be derived. See for instance Bloch (2003) and Yi (2003).

assumed. The only exceptions are ROW in case of no transfers and ROW and JPN in case of transfers. The highest valuation from a region's point of view are indicated bold in Table 1.

It is evident that superadditivity and positive externality are sufficient (though not necessary) conditions that aggregate welfare across all players increases through cooperation. That is, given a coalition structure c, whenever single regions or non-trivial coalitions merge, global welfare is raised. That is, cooperation is globally rational - a central property that provides a strong normative motivation for the analysis of self-enforcing agreements in the presence of free-rider incentives in global pollution control.

The third property is called individual rationality (IR) and means that a region receives a (weakly) higher valuation than in the coalition structure with only singletons.

Property 3: Individual Rationality

A coalition structure $c \in C$ *with associated valuation* $v(c) \in V(C)$ *is individually rational if and only if for all* $i \in N: v_i(c) \geq v_i(c^N)$ *where* $c^N = \{\{1\},...,\{n\}\}$ *is the coalition structure with only singletons.*

Individual rationality is a necessary condition for the participation of a region in a non-trivial coalition because by remaining a singleton a region receives at least its valuation in the coalition structure with only singletons due to positive externalities. In the case of no transfers, it is evident from Table 1 that some coalition structures are not individually rational to all parties. Examples include the grand coalition with rank No. 1 and the coalition structure No. 2 which are not individually rational for FSU, provided there are no transfers.

The reason for the lack of individual rationality is that joint welfare maximization may imply an asymmetric distribution of the gains from cooperation. For instance, in CWSM, FSU benefits little from cooperation because of her flat marginal damage cost function. Moreover, due to her flat marginal abatement cost function she has to contribute much to cooperative efforts to curb emissions. However, with transfers, all valuations $v^T(c) \in V^T(C)$ are IR. Due to SAD, the term in square brackets in our transfer formula (2) is always positive and hence $v_i^T(c) \geq v_i(c^N)$ for all regions that are members of a non-trivial coalition. As observed above, for all singletons $v_i(c) = v_i^T(c) \geq v_i(c^N)$ holds anyway because of PEX. Note that the set of IR coalition structures is never empty because the coalition structure with only singletons is IR by Definition 3.

The fourth property is called Pareto-optimality (PO). A coalition structure is PO if there is no other coalition structure where at least one region is better off and no other region is worse off.

Property 4: Pareto-optimality

A coalition structure $c \in C$ *with associated valuations* $v(c) \in V(C)$ *is Pareto-optimal with respect to* $V(C)$ *if there is no other coalition structure* $\tilde{c} \in C$ *with* $v(\tilde{c}) \in V(C)$ *such that* $v_i(\tilde{c}) \geq v_i(c)$ $\forall i \in I \wedge \exists j \in I$: $v_j(\tilde{c}) > v_j(c)$.

This definition is the well-known definition of Pareto-optimality applied to the context of coalition formation. Note that PO relates only to a particular set of valuations, i.e. in our context either to $V(C)$ without transfers or to $V^T(C)$ with transfers. Though PO coalition structures are not indicated in Table 1, it easily checked that coalition structure No. 152 is Pareto-dominated by the grand coalition with rank No. 1 and coalition structures No. 173, 195 and 203 are Pareto-dominated by coalition structure No. 3 where this holds with and without transfers. Obviously, the grand coalition is always a PO - regardless whether we consider $V(C)$ or $V^T(C)$ - because it generates the (strictly) highest global welfare. It is also evident that the singleton coalition structure can never be a PO if a transfer scheme guarantees individual rationality as applies to $V^T(C)$ as argued above.

Property 5: Strict Individual Preferences

Players have strict individual preferences over coalition structures if and only if for every pair of distinct coalition structures $c \in C$ *and* $\tilde{c} \in C$ *with* $c \neq \tilde{c}$ *it holds that:* $\forall\, i \in I$: $v_i(\tilde{c}) > v_i(c)$ *or* $v_i(\tilde{c}) < v_i(c)$.

Our last property is called strict individual preferences (SIP). It implies that every player can rank coalition structures according to his valuations in the entire set of coalition structures. In other words, players are never indifferent between two different coalition structures. SIP is mainly a technical property which holds for CWSM and eases the determination of equilibrium coalition structures.

4. First Stage of Coalition Formation

4.1 Original Game

Based on valuations, either on valuations with or without transfers, $V(C)$ or $V^T(C)$, derived in the second stage of coalition formation, players decide upon participation in coalitions in a sequential process. The process is modeled based on the sequential move unanimity game (SMUG) of Bloch (1995), though for our purposes some changes are necessary which we discuss below. This game is in the spirit of Rubinstein´s (1982) two-player alternating offers bargaining game and is a generalization of Chatterjee et al.´s (1993) extension to an n-player bargaining game. The SMUG assumes that players are ordered according to some rule. The player with the lowest index (initiator), say, player 1, starts by announcing a list of coalition members including himself. Every member on the list is asked whether he or she accepts the proposal. The player with the lowest index on this list is asked first, then the player with the second lowest index and so forth. If all players on the list agree, the coalition, say, c_1, is formed and coalitions among the remaining players $I \setminus c_1$ may form. The player with the lowest index among $I \setminus c_1$ becomes the new initiator. If a player rejects a proposal, he can make a new proposal.

Thus, a coalition only forms by unanimous agreement. Because a player can always reject a proposal, participation in a non-trivial coalition is voluntary. Both features are well in line with the institutional setting of international environmental agreements. It is also evident that players whose proposals have been turned down are still part of the formation process. They may become members of other coalitions than those they have proposed. Also players that have turned down a proposal are still part of the game since they can propose a new coalition. Only if n-1 players have already formed a coalition, the last remaining player will have no other choice than to become a singleton. When the negotiation process terminates, all players receive their payoffs.

For simplification, Bloch (1995, 1996) assumes no discounting of valuations during this process. He also assumes that players who cannot agree on a coalition receive a payoff which is Pareto-dominated by payoffs in every coalition structure. Thus, the solution to the game becomes "finite". Moreover, he only considers stationary perfect equilibrium strategies in order to reduce the amount of possible equilibria. That is, strategies only depend on the current state (and not on the entire history of the game) in the negotiation process of which there are basically three:

1) There is an ongoing proposal which the player who moves may accept or reject.

2) A player has rejected a proposal and makes a proposal himself.

3) A coalition has formed and a player becomes the new initiator.

Therefore, the payoff relevant part of the history at some stage is the set of players who have left the game already, the partition they have formed and the current offer. A sequence of proposals is a perfect equilibrium if proposals and reactions to proposals are mutually best replies for each possible state in the remaining game.

To the best of our knowledge, until now, Bloch´s game has only be applied to economic problems with the assumption that all players have the same payoff function.[6] For ex-ante symmetric players as this assumption has been termed in the literature, Bloch (1996) has shown that things simplify substantially since the identity of players does not matter and – in most economic examples of interest - payoffs to a player only depend on the sizes of his own and the remaining coalitions in a given coalition structure c.[7] Hence, the sequence in which players make proposals and counter-proposals, as well as the sequence according to which players are asked for acceptance does not matter for the outcome of coalition formation. Moreover, a proposal means to announce the size of a coalition to which the proposer wants to belong and hence the entire game reduces to a "size announcement game" in which the interests of the proposer and the members of the coalition that she proposes always coincide.

Clearly, some simplifications would not be appropriate in our context, in particular as we have not only ex-post but also ex-ante different players. Therefore, we discuss in the next section some problems related to the implementation and solution of the SMUG and the valuations derived from the CWSM.

4.2 Issues of Implementation

There are three issues that have to be discussed for the implementation and the solution of the SMUG in our empirical context.

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6 See Bloch (2003) for an overview. Bloch's game has been applied for instance by Finus and Rundshagen (2006a) and Ray and Vohra (2001) in the context of the provision of public goods; both applications assuming symmetric players.

7 For instance, in a global emission abatement game with a static payoff function Finus and Rundshagen (2003) have shown that, in a given coalition structure, members of larger coalitions receive a lower valuation than members of smaller coalitions because all players receive the same benefits from global abatement but members of larger coalitions choose higher individual abatement levels and therefore have higher abatement costs.

Sequence of Proposals

Bloch assumes that players are indexed according to some exogenous rule. Though for ex-ante symmetric players this sequence has no effect on the outcome, it will be crucial for asymmetric players. The sequence is an essential element in the strategic considerations of players and affects for instance decision whom an initiator approaches first. However, the crucial question arises how the first initiator is determined and who will be the subsequent initiator if a coalition has formed? Intuitively, one may want to endogenize this sequence, making it part of the bargaining game itself.

It could be argued for instance that the first initiator is the player who gains most from cooperation. However, then the question arises how this gain is computed? One reference point could be the valuation without any cooperation but the second reference point is anything else than obvious. Is it the valuation that a player receives on average from cooperation if he is a member of a coalition and is the gain measured in absolute or relative terms? However, the average is also not convincing because this would include valuations of coalition structures that may never emerge as an equilibrium. But also the average of valuations over all equilibrium coalition structures for all possible index sequences is not an innocuous selection criterion for several reasons but in particular not because equilibria depend on the sequence itself and hence there is a feedback relation that seems difficult to solve.

We will not pursue this discussion here, noting that this issue might be an important topic for future research, though beyond the scope of this paper. Instead, we stick to the original proposal of Bloch. We solve for the equilibrium coalition structure for every possible index sequence of which there are 720 in the case of six players. The analysis of our results in section 5 will focus on the effect of different sequences on the outcome of coalition formation. Important questions will be for instance: which regions should be among the initiators in order to induce successful cooperation from a global point of view? Is it an advantage to be an initiator or is a wait-and-see-strategy more promising for individual regions? Moreover, in section 5, we will analyze whether a moderator, though without enforcement power, can influence the outcome by coordinating the sequence in the negotiations.

Cycles of Proposals

Generally, the bargaining game may have an infinite horizon and therefore may have no solution. Suppose players have very different preferences about their most preferred outcome. Then if all players insist on their most preferred outcome, this may lead to an infinite number of proposals and rejections. As mentioned, a simple way of avoiding those cycles is to assume that if players do not agree in finite time, they will end up with a Pareto-inferior outcome compared to the valuations of all possible coalition structures. Though this may seem an elegant solution in a theoretical setting, we think it is not appropriate in our empirical setting for two reasons.

First, viewing the coalition structure with only singletons as the starting point of negotiations, there seems to be no plausible reason why regions should not receive at least this payoff if negotiations fail. One way out of the dilemma of cycles could be discounting. Apart from the question which discount rates are appropriate and which discount rates avoid cycles, this would raise some other conceptual questions. For instance, does time elapse after a player has been asked for acceptance or after a player has rejected a proposal? Moreover, given that in our context valuations are derived from a dynamic integrated assessment model, it would not be consistent to discount valuations only. Instead, this required that also equilibrium economic strategies would have to be revised if time passes by. It is evident that this would be an interesting and certainly fruitful approach of modeling negotiations over climate policy but is beyond the scope of this paper.

We follow a pragmatic approach that is inspired by software programs modeling chess and other games. At the time of an ongoing proposal and as long as no additional coalition has formed, the same player cannot make a second proposal if her first proposal has been turned down. It is important to note that this rule only applies if the game does not proceed. If a coalition has eventually formed at stage t, this player can again make a proposal at $t+1$ (provided she has not accepted already another proposal).

Second, solving the game with an algorithm requires a well defined amount of finite branches. Our pragmatic solution ensures this whereas this would not be true for many other possible assumptions, like discounting. The strategic implications are illustrated with simple examples in subsection 4.4.

Indifference of Proposals

Generally, valuations of different coalition structures may be identical for some players. Hence, the equilibrium path in the SMUG would not be uniquely determined. In a theoretical setting with only few players this problem can certainly be ignored by just computing all equilibria. In our context of six players, however, this would increase computation time tremendously. Fortunately, we can ignore this problem because for our data set all players have a strict individual preference overall all valuations, with and without transfers (see section 3.2, property 5).

4.3 Description of the Algorithm

As argued above, we have to modify Bloch's coalition game SMUG slightly, which we call Finite Sequential Move Unanimity Game (FSMUG). As the SMUG has already been described in much detail in subsection 4.1, and relevant issues of implementation in subsection 4.2, we only add some final definitions and briefly comment on the algorithm that we use for solving for equilibrium coalition structures.

We order players, i.e. regions in CWSM, randomly and then generate all permutations. That is, the index number of player i is $\pi(i)$ with $\pi : I \to I$ denoting the corresponding permutation. In the case of n players, there are $n!$ permutations. At any node in the game tree, the history h^t contains the following payoff relevant information which describes the state of the game:

- a set $\hat{K}$ of players who have already formed coalitions,
- a coalition structure $\hat{c}$ formed by the players of $\hat{K}$,
- an ongoing proposal (if any) $\hat{T}$,
- a set $\hat{A}$ of players who have already accepted the proposal,
- the player $\hat{a}$ who moves at node t,
- the initiator $\hat{i}$ of the ongoing proposal and
- the set of players $\hat{I}$ who may become initiators during the formation process of the next coalition.

The last two items distinguish the FSMUG from the original SMUG by Bloch because we assume that an initiator can make only one proposal as long as no further coalition has been formed. Like in Bloch (1995), the relevant history at time t, h^t, depends only on the current state of the game at time t (and not on the entire history of the game). Hence, equilibrium coalition structures are derived as stationary perfect equilibrium which is a vector of strategies for all players such that, after each relevant history of the game, all players choose an optimal action.

The algorithm is visualized in Appendix 2. It is a backtracking algorithm along the lines for instance described in Alho et al. (1987). The algorithm is programmed in Java, version 1.4.2.

4.4 Properties and Strategies

We first briefly and informally show that our FSMUG - applied to our valuations $V(C)$ and $V^T(C)$ derived from CWSM - possesses some essential properties which are important for determining equilibrium coalition structures. Then, we illustrate some interesting implications for the optimal strategies of players. For this we use simple examples with three players as the driving forces would be difficult to trace in our application with six players.

First note that an equilibrium in the FSMUG always exists and the equilibrium coalition structure is unique for given index sequence. This follows from three items: a) the game tree is finite by construction, b) there is perfect information with respect to the history of the game and hence every information set consists of only one decision node and c) at every decision node an active player is only indifferent between two or more actions if the equilibrium coalition structures of the subgame coincide because every player has a strict preference order over all coalition structures (i.e. property 5: SIP in section 3.2 holds).

Second note that all equilibria (e.g. emerging from different index sequences or different sets of valuations) will be individually rational. Regardless of the coalition which has formed in the game, a player i can always remain a singleton by proposing coalition $\{i\}$, which ensures him at least the payoff in the singleton coalition structures due to the positive externality (i.e. property 2: PEX in section 3.2 holds).

Example 1 in Table 2 shall illustrate the interesting phenomenon that a player may intentionally put forward a proposal that she knows will be turned down. First note that players 2 and 3 derive their highest valuation when the other two players form a coalition and they free-ride. Hence, if either player 2 or 3 is the initiator, they propose a single coalition. Since the singleton coalition structure c^1 is Pareto-dominated by all other coalition structures, the remaining players will form a coalition of two players. Thus, if player 2 is the initiator $c^3 = \{\{1,3\},\{2\}\}$ and if player 3 is the initiator, $c^2 = \{\{1,2\},\{3\}\}$ will emerge as the equilibrium coalition structure.

Example 1: Provoked Non-Acceptance Game

Coalition Structure	$v_1(c)$	$v_2(c)$	$v_3(c)$	$\sum_{i=1}^{3} v_i(c)$
$c^1 = \{\{1\},\{2\},\{3\}\}$	0	0	0	0
$c^2 = \{\{1,2\},\{3\}\}$	2	2	8	12
$c^3 = \{\{1,3\},\{2\}\}$	8	8	2	18
$c^4 = \{\{1\},\{2,3\}\}$	4	4	4	12
$c^5 = \{\{1,2,3\}\}$	7	7	7	21

A more interesting strategy is observed when player 1 is the initiator. Her most preferred coalition structure is $c^3 = \{\{1,3\},\{2\}\}$. However, suppose she proposed this, then player 3 would turn down her offer and would simple propose $\{3\}$. Now, player 1 and 2 would have no better option than to agree on forming a coalition together and hence $c^2 = \{\{1,2\},\{3\}\}$ would form which is player 1's second worst option. Thus, player 1 proposes $\{1,2\}$ which she knows will not be accepted by player 2. That is, she passes on the right to make a proposal to player 2, knowing that he will act in her best interest: player 2 will propose $\{2\}$ so that player 3 has to give in and forms a coalition with player 1. Hence, $c^3 = \{\{1,3\},\{2\}\}$ emerges as the equilibrium. In other words, players 1 and 2's interest are in line and player 1 can only get her way be letting player 2 make the first effective move. Hence, $c^3 = \{\{1,3\},\{2\}\}$ is the equilibrium if player 1 is the initiator.

Example 1 also illustrates that the equilibrium outcome depends on the sequence of players. Moreover, moving first can be associated with an advantage. Regardless who kicks off the game, she can implement her most preferred coalition structure. That this is not always the case will be illustrated in example 2 below.

In example 2 there are only two Pareto-undominated coalition structures, namely c^2 and c^5. Coalition structure c^2 is the most preferred outcome of player 1 and c^5 of players 2 and 3. Suppose player 1 is the initiator. If he proposed $\{1,2\}$, and player 2 accepted, then c^2 would form. However because c^2 is only player 2's second best option, and player 2 and 3 both prefer the grand coalition c^5, player 2 could propose the grand coalition. Given that player 1 cannot make a new proposal as long as the game has not proceeded, and the grand coalition Pareto-dominates the singleton coalition structure c^1, player 1 would have to accept this proposal. However, c^5 is only player 1's third-best alternative. Consequently, player 1, anticipating all this, proposes $\{1\}$ in equilibrium, knowing that players 2 and 3 prefer to form a coalition together instead of remaining singletons. Thus, the equilibrium coalition structure if player 1 is the initiator (regardless how players 2 and 3 are ordered), is coalition structure $c^4 = \{\{1\},\{2,3\}\}$.

Example 2: Pareto-dominated Equilibrium Game

Coalition Structure	$v_1(c)$	$v_2(c)$	$v_3(c)$	$\sum_{i=1}^{3} v_i(c)$
$c^1 = \{\{1\},\{2\},\{3\}\}$	0	0	0	0
$c^2 = \{\{1,2\},\{3\}\}$	6	2	4	12
$c^3 = \{\{1,3\},\{2\}\}$	1	1	1	3
$c^4 = \{\{1\},\{2,3\}\}$	5	1	3	9
$c^5 = \{\{1,2,3\}\}$	3	6	5	14

Since c^4 is Pareto-dominated by c^2, this example illustrates that there are instances where a Pareto-dominated equilibrium coalition structure can emerge as an equilibrium due to strategic considerations. Moreover, it shows that an initiator cannot always push through her most preferred outcome. This is also the case if either player 2 or 3 are the initiators, though in this case a Pareto-optimal coalition structure (i.e. c^2) is the equilibrium outcome.

If either player 2 or 3 moves first, they anticipate that they cannot enforce their most preferred coalition structure c^5 as player 1 will raise objections. Hence, both players try to enforce their second-best option which is c^2 and which they know will be accepted by player 1, as it is his first-best option. Hence, if player 2 is the initiator, he will propose $\{1,2\}$, which player 1 will accept, leaving player 3 as a singleton. If player 3 is the initiator, she proposes $\{3\}$ and player 1 and 2 form $\{1,2\}$.

Thus, if either player 2 or 3 is the initiator, they cannot implement their first choice as an equilibrium (as this is the case if player 1 is the initiator). Even more important, they make proposals which lead to the most preferred coalition structure of player 1. In other words, from player 1's point of view, there is an advantage not to move first.

5. Results

In this section we display and discuss equilibrium coalition structures based on the valuations in CWSM. We start with the standard assumption which means that there is no moderator (section 5.1). We then have a look whether a moderator can change the outcome through coordinating actions among regions, though without being equipped with enforcement power (section 5.2).

5.1 Without Moderator

Table 2 displays equilibrium coalition structures for the case of no transfers and the case of transfers. In the case of no transfers, there are 11 equilibrium coalition structures, in the case of transfers, there are only two. Equilibrium coalition structures are sorted according to welfare at the world level in descending order. The ranks for different regions within the set of equilibria are indicated in the columns under the heading "Ranking". The first entry in the column "PO" indicates whether the coalition structure is Pareto-undominated among the entire set of coalition structures of which there are 203. The second entry in this column indicates whether the coalition structure is Pareto-undominated among the set of equilibrium coalition structures. The frequency of occurrence of a coalition structure among the 720 possible index sequences is indicated in the last column.

Table 2 about here

We would like to point out four general observations. First, equilibrium coalition structures emerge that are not a PO among the set of possible coalition structures. This possibility was illustrated in example 2 in section 4.4 and is due to the strategic characteristics of the coalition formation game. As in example 2, this even occurs if Pareto-dominance is only checked among the set of equilibrium coalition structures. As we will illustrate, this last remark is the motivation to analyze the role of a moderator.

Second, nearly all equilibrium coalition structures include multiple non-trivial coalitions. Hence, if players have not only the option to join an agreement or to remain a singleton, coalition structures with multiple coalitions emerge in equilibrium. This observation is in line with simulation results for instance in Finus et al. (2009) and Eyckmans and Finus (2006) and the theoretical findings in Carraro (2000) and Finus and Runsdhagen (2003), though they assume a simultaneous coalition formation process under various membership rules. The relative high average CGX is due to the fact that the FSMUG de facto implies that a coalition only forms if and only if all players unanimously agree to form exactly this coalition. That is, a high degree of unanimity is conducive to the success of coalition formation as spelled out for instance in Eyckmans and Finus (2006) and Finus and Rundshagen (2006b). However, the grand coalition is not stable.

Third, transfers lead to a higher average CGX than no transfers. Transfers seem to align interests more among heterogeneous players for our data set, as they lead to a more symmetric distribution of the gains from cooperation (at least all coalition structures are individually rational), which leads to one equilibrium coalition structure in 98 percent of the possible index sequences. This is different for no transfers where the index sequence matters much more. Nevertheless, also here the first three ranked equilibrium coalition structures (which are Pareto-undominated) appear with a frequency of 599 all together, amounting to 83 percent of the possible index sequences. All together, we confirm the positive effect of transfers for the success of coalition formation that has been found for simultaneous coalition formation games. See for instance Botteon and Carraro (1997), Carraro et al. (2006), Eyckmans and Finus (2006), Weikart et al. (2006) among many others.

Fourth, irrespective whether we consider no transfers or transfers, there is no equilibrium coalition structure which is the most preferred for a particular region among the entire set of coalition structures.[8] In other words, no region, regardless of the sequence in which they make proposals, can enforce its most preferred coalition structure. A similar conclusion, though less pronounced emerges from Table 3.

Table 3 looks at the most preferred and least preferred equilibrium from a region's point of view among the set of equilibrium coalition structures. Percentages indicate the frequency that region i is among the first three in the index sequence when this equilibrium emerges. For instance, USA's most preferred equilibrium for no transfers is the first equilibrium coalition structure displayed in Table 2. It occurs 32 times. In 30 instances, the USA is among the first three players and hence 30/32=93.8%. Thus, the USA has a first mover advantage when it comes to her most preferred equilibrium. Similarly, USA's worst equilibrium is ranked no. 10 at the world scale (see Table 2, no transfers). It occurs 78 times and in 12 instances the USA is among the first three players and hence 12/78=15.4%. Put differently, in 84.6% of the cases the USA can not avoid the worst outcome because of her late mover position. This relation can be interpreted as a first mover advantage to avoid bad outcomes.

The other entries for other regions in Table 3 are computed in the same way. Hence, in row "Best Equilibrium", a percentage above 50% indicates a first mover advantage (indicated bold) and in row "Worst Equilibrium" this is true for a percentage below 50% (indicated bold). Thus, only in the case of transfers there seems to be on average a first mover advantage. This is in line with our example 2 in section 4.4 which showed that it is not always in the interest of a player to move first, i.e. there may be a last or later mover advantage. It appears that – on average - there is a first-mover advantage to avoid the worst outcome.

In the context of the provision of a public good, two incentives can roughly be identified to explain this, though incentives are far more complex for the valuations derived from CWSM. On the one hand, moving first provides the possibility to free-ride by either proposing to remain a

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8 This is evident by comparing Table 1 and 2.

singleton or being only a member of a small coalition. This, however, requires that the player can expect that others cooperate if he commits to little cooperation. On the other hand, it can also be advantageous to move later in the game, hoping that others commit to cooperation. In a simple symmetric player context and public good provision Finus and Rundshagen (2006a) have shown that only the first incentive is at work.[9] Now, in the case of heterogeneous players, obviously, also the second incentive seems to be relevant in some instances.

5.2 With Moderator

Until now, we assumed that there is no third party that can enforce cooperation. This is in line with the institutional setting in which IEAs operate. In the following, we do not give up this assumption, but consider that a third party may act as a moderator by coordinating action. Thus, the moderator can only make recommendations to the various parties. From a policy perspective, analyzing the role of a moderator seems suggestive as many international organizations like the World Bank, the United Nations with its environmental program or the International Panel on Climate Change (IPCC) are involved in climate negotiations. From a game theoretic point of view we have seen that some equilibrium coalition structures are Pareto-dominated, even in the set of equilibrium coalition structures. Hence, it seems natural to ask the question whether a moderator can improve upon these outcomes.

In actual negotiations, international organizations perform many and complex tasks. However, in our model, we consider this role only in a very stylized and therefore simplistic way. Nevertheless, we believe that our analysis highlights the importance of moderators for future climate negotiations. Not only from a normative point of view, but also from a positive perspective there is a need to explain the existence of international organizations.

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[9] In example 1 in section 4.4, this free-rider incentive could also be observed if either player 2 or 3 moves first, though the game is not symmetric.

Without moderator and further a priori information, it seems reasonable to expect that each index sequence is equally likely to occur. If we let $v_i(c^*)$ denote the valuation by player i from equilibrium coalition structure c^* (of which there are for instance 11 in the case of no transfers; see Table 2), the frequency with which coalition structure c^* emerges among the $n!$ possible permutations of players (i.e. possible index sequences) by $FR(c^*)$, then the probability that equilibrium coalition structure c^* emerges is $p(c^*) = FR(c^*)/n!$ and the expected valuation of player i in the FSMUG is simply $E(v_i) = \sum_{c^* \in C^*} p(c) \cdot v_i(c^*)$ with C^* the set of equilibrium coalition structures. The total expected valuation is $\sum_{i=1}^{n} E(v_i)$, which can be interpreted as the average aggregate welfare. In Table 2 this value was expressed in relative terms as average CGX (e.g. $\varnothing = 77.3$ in the case of no transfers).

Now we assume that the moderator can propose probabilities different from $p(c^*)$ which we denote $z(c^*)$. We assume that the aim of the moderator is to maximize total expected valuation subject to the constraint that no player is worse off accepting this proposal.

$$(3) \qquad max \sum_{c^* \in C^*} \left(z(c^*) \sum_{i=1}^{n} v_i(c^*) \right)$$

$$\text{s.t.} \sum_{c^* \in C^*} z(c^*) v_i(c^*) \geq E(v_i) \quad \forall\, i \in \{1,\ldots,n\}$$

$$0 \leq z(c^*) \leq 1 \quad \forall\, c^* \in C^* \ \ and \sum_{c^* \in C^*} z(c^*) = 1$$

Since $v_i(c^*)$ and $E(v_i)$ are constants and the objective function as well as all constraints are linear, this is a standard linear programming problem. The solutions $z(c^*)$ will not differ from $p(c^*)$ if, as in the case of transfers in Table 2, there are only two coalition structures of which none Pareto-dominates the other. However, in the case of no transfers, this is different and the moderator can raise expected welfare from $\varnothing CGX = 77.3$ to $\varnothing CGX = 80.4$. The moderator will attach to all Pareto-dominated equilibrium coalition structures within the set of equilibria, a probability of zero. Moreover, all equilibrium structure that are Pareto-dominated by a combination of other equilibrium coalition structures also receive probability zero. This implies in the case of no transfers that to only two out of 11 equilibrium coalition structures a probability $z(c^*) > 0$ is attached, which are the first two coalition structures listed in Table 2.

5.3 Sensitivity Analysis

Since our results have been obtained by simulations, we test the robustness of our conclusions. As appears from the discussion in the previous sections, we are not interested in quantitative results, but in qualitative conclusions. This seems suggestive given the large uncertainty surrounding the calibration of the parameters of integrated assessment models. Among the main parameters that enter CWSM, we focus on a variation of the discount rate as there has been much debate about the appropriate choice of the discount rate (time preference rate). Hence, we consider instead of $\delta = 0.01$ (see Appendix 1) also two other values, $\delta = 0.02$ and $\delta = 0.03$, for which we produce tables in the spirit of Tables 2 and 3 and which are available upon request. From this sensitivity analysis the following conclusions can be drawn.

Despite some equilibrium coalition structures differ, all other conclusions are very robust. Average success rates measured as average CGX remain very similar. The general observations mentioned in section 5.1 also remain true. Equilibrium coalition structures emerge that are not Pareto-optimal among the entire set of coalition structures and some are even Pareto-dominated by other equilibrium coalition structures, and this happens more frequently in the absence of transfers.

Nearly all equilibrium coalition structures comprise multiple non-trivial coalitions and transfers lead to a higher average CGX, at least if a moderator supports negotiations. Regions can never push through their most preferred coalition structure regardless of the sequence in the negotiations, though there is now one exception: FSU. However, interestingly, when this most preferred coalition structure emerges, the percentage of instances in which FSU is among the first three regions in the index sequence is below 50%, suggesting that there is no first but a later mover advantage for FSU. Also for other players there is no indication of first-mover advantage on average concerning their most preferred outcome, suggesting that a wait-and-see-strategy can be attractive to the participants in climate negotiations.

6. Summary and Conclusions

We combined two modules, an empirical model on climate change and a game theoretic model of coalition formation, to study self-enforcing climate agreements. The empirical model was the Climate Change World Simulation Model (CWSM), version 1.2, which is a dynamic optimal growth model that captures the feedback between the economy and climate change for six world regions. We computed payoffs for all possible partitions of players, called valuations, allowing for the possibility of the co-existence of several coalitions. Based on these valuations, we determined stable coalition structures.

We considered two new conceptual issues of coalition formation in the context of IEAs. The first issue was the sequential coalition formation process as such. This novelty was motivated by the empirical evidence that participation in IEAs have evolved sequentially in the past. We argued that the sequential move unanimity game proposed by Bloch (1995) has to be modified for practical purposes in order to avoid infinite cyclical proposals. We introduced the assumption that a player whose proposal has been turned down, cannot make a second proposal as long as the formation process has not proceeded. This allowed us to develop a backtracking algorithm to solve for equilibrium coalition structures. The second issue was the analysis of a moderator who coordinates the negotiation process but can only make recommendations which are self-enforcing and Pareto-improving to all parties. This novelty was motivated by positive and normative arguments. Among those were the empirical evidence that many international organizations play some role in shaping and coordinating IEAs, but the scientific literature could not yet provide a rationale for their existence and their role. Moreover, even if we acknowledge the fact that these organizations have no enforcement power, it is important to explore whether and how they can foster international cooperation which is desperately needed to address for instance the problem of global warming.

One part of our results illustrated the strategic properties of a sequential coalition formation process. For instance, we showed that there is not always a first-mover advantage, but a wait-and-see-strategy may well pay. Negotiators may even have an incentive to put forward a proposal which they know will be turned down in order to benefit from a later mover advantage. Due to strategic considerations and strong free-rider incentives, equilibrium coalition structures may not be Pareto-optimal. It also clearly emerged that it is very unlikely that single negotiators can push through their most preferred outcome, irrespective of the sequence when they move.

Another part of the results confirmed conclusions derived from a simultaneous coalition formation process. Due to large asymmetries across the world in the climate change context in terms of the environmental damages and abatement cost, compensation payments are conducive to establish effective cooperation. Moreover, if participation is not restricted exogenously to a single agreement, multiple coalitions will emerge as equilibrium outcomes. As argued for instance in Eyckmans and Finus (2006) and Finus et al. (2009), this may be taken as indication to revise previous policy strategies. As long as free-rider incentives do not allow forming a climate agreement with full participation, it may be worthwhile to allow for bilateral agreements instead of focusing on a single treaty. Finally, we showed that if multiple equilibria exist, a moderator may play an important role by helping to avoid bad outcomes.

From our results two main avenues for future research emerge. First, the role of moderators and coordinators for shaping IEAs should be explored further. The aim should be to model this in a less stylized way as we did and to explore the possibilities available to international organizations to play a constructive role in initiating IEAs, coordinating negotiations and helping to formulate ambitious though realistic policy goals as well as implementing and monitoring agreements. Second, more conceptual work is needed to capture the dynamic nature of the formation of IEAs in terms of participation, policy goals, enforcement and the stock pollutant nature of greenhouse gases. This is certainly a non-trivial challenge but would help to base policy recommendations for the design of successful future IEAs on a more realistic basis. After all, it is not to be expected that problems like climate change, the depletion of the ozone layer or biodiversity will disappear in the future.

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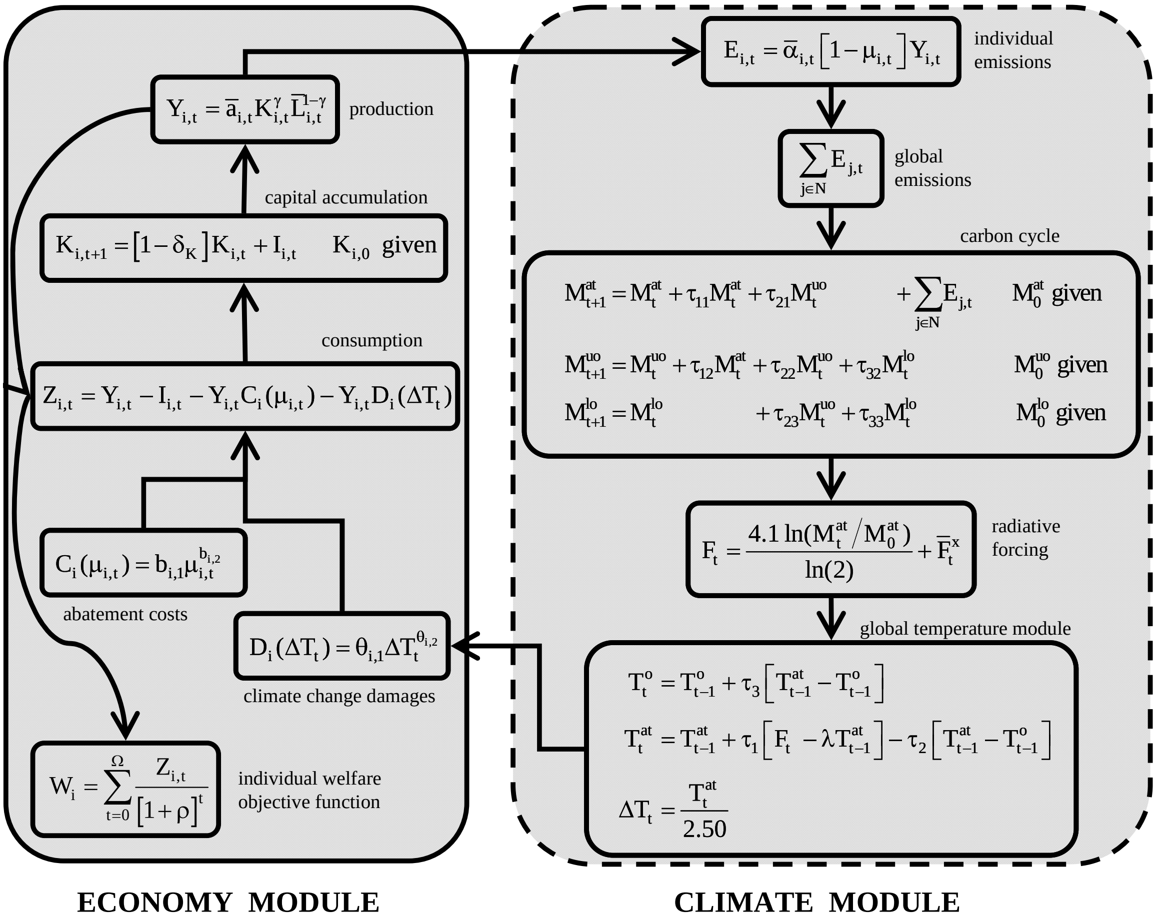
Appendix 1

Figure A.1 shows the CLIMNEG World Simulation Model[10], version 1.2, which consists of two main blocks of equations: the economy (left) and the climate module (right). Subindices t denote time (in steps of 10 years[11]) and indices i indicate the region. Exogenous processes are indicated by an overbar.

Figure A.1: Schematic Overview of CLIMNEG World Simulation Model



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10 The GAMS code for the simulations is available from the authors upon request, including the entire matrix of valuations.

11 In order to save space, the equations shown in Figure A.1 are simplified to an annual representation of the stock variables' accumulation processes. Using a time step different than one year, alters slightly the look of these equations but does not affect the essential aspects of the processes.

Table A.1: List of Variables and Functions

$Y_{i,t}$	production (billion $US\$_{2000}$)
$Z_{i,t}$	consumption (billion $US\$_{2000}$)
$I_{i,t}$	investment (billion $US\$_{2000}$)
$K_{i,t}$	capital stock (billion $US\$_{2000}$)
$E_{i,t}$	carbon emissions (billion tons of carbon, btC)
$\mu_{i,t}$	emission reduction (between zero and one)
$C(\mu_{i,t})$	emission reduction cost function (fraction of GDP, between zero and one)
ΔT_t	global mean temperature change (°C)
$D_i(\Delta T_t)$	climate change damage function (fraction of GDP, between zero and one)
W_i	welfare measured as aggregated discounted consumption
M_t^{at}	atmospheric carbon concentration (btC)
M_t^{uo}	carbon concentration in upper strata ocean (btC)
M_t^{lo}	carbon concentration in lower strata ocean (btC)
F_t	radiative forcing (Watt per m^2)
T_t^{at}	atmospheric temperature (°C)
T_t^{0}	lower ocean temperature (°C)

Table A.2: Global Parameters

$\bar{a}_{i,t}$	Productivity	exogenous	
$\bar{L}_{i,t}$	Population	exogenous	
$\bar{\alpha}_{i,t}$	emission-output rate	exogenous	
$\bar{F}_t^x$	Exogenous radiative forcing	exogenous	
δ_K	annual rate of capital depreciation	0.10	
γ	capital productivity parameter	0.25	
ρ	annual rate of time preference	0.01*	
Ω	terminal year	2330	
τ_{11}	parameter carbon cycle	-0.033384	
τ_{12}	parameter carbon cycle	0.033384	
τ_{21}	parameter carbon cycle	0.027607	
τ_{22}	parameter carbon cycle	-0.039103	
τ_{23}	parameter carbon cycle	0.011496	
τ_{32}	parameter carbon cycle	0.000422	
τ_{33}	parameter carbon cycle	-0.000422	
τ_1	parameter global temperature module	0.226	
τ_2	parameter global temperature module	0.440	
τ_3	parameter global temperature module	0.020	
λ	parameter global temperature module	1.410	
M_0^{at}	Initial (=2000) atmospheric carbon concentration	783	btC
M_0^{uo}	Initial (=2000) carbon concentration in upper strata ocean	807	btC
M_0^{lo}	Initial (=2000) carbon concentration in lower strata ocean	19238	btC
T_0^{at}	Initial (=2000) atmospheric temperature	0.622	°C
T_0^{0}	Initial (=2000) lower ocean temperature	0.108	°C

* The sensitivity analysis is conducted for values 0.02 and 0.03.
Details for the time path of exogenous parameters and calibration of carbon cycle and temperature module are available from the authors upon request.

Table A.3: Regional Parameters

	$\theta_{i,1}$	$\theta_{i,2}$	$b_{i,1}$	$b_{i,2}$
USA	0.01102	2.0	0.07	2.887
JPN	0.01174	2.0	0.05	2.887
EU	0.01174	2.0	0.05	2.887
CHN	0.01523	2.0	0.15	2.887
FSU	0.00857	2.0	0.15	2.887
ROW	0.02093	2.0	0.10	2.887

Source: RICE_96 model by Nordhaus and Yang (1996).

Table A.4: Regional Initial (=2000) Data

	$Y_{i,0}$	$L_{i,0}$	$K_{i,0}$	$E_{i,0}$
USA	7563.810	282.224	19740.689	1.574
JPN	3387.931	126.87	9753.970	0.330
EU	8446.901	377.136	22804.477	0.888
CHN	968.906	1262.645	2686.056	0.947
FSU	558.436	287.893	1490.038	0.626
ROW	6633.427	3715.663	14105.209	2.192
WORLD	27559.411	6052.431	70580.438	6.556
	billion US$$_{2000}$ (market exchange rate)	million people	billion US$$_{2000}$	billion tons carbon btC (fossil fuel use)

Source: World Resources Institute http://www.wri.org (for $Y_{i,0}$ and $E_{i,0}$), UN Economic and Social Affairs division (for $L_{i,0}$) and own calibration (for $K_{i,0}$). Details are available from the authors upon request.

Appendix 2

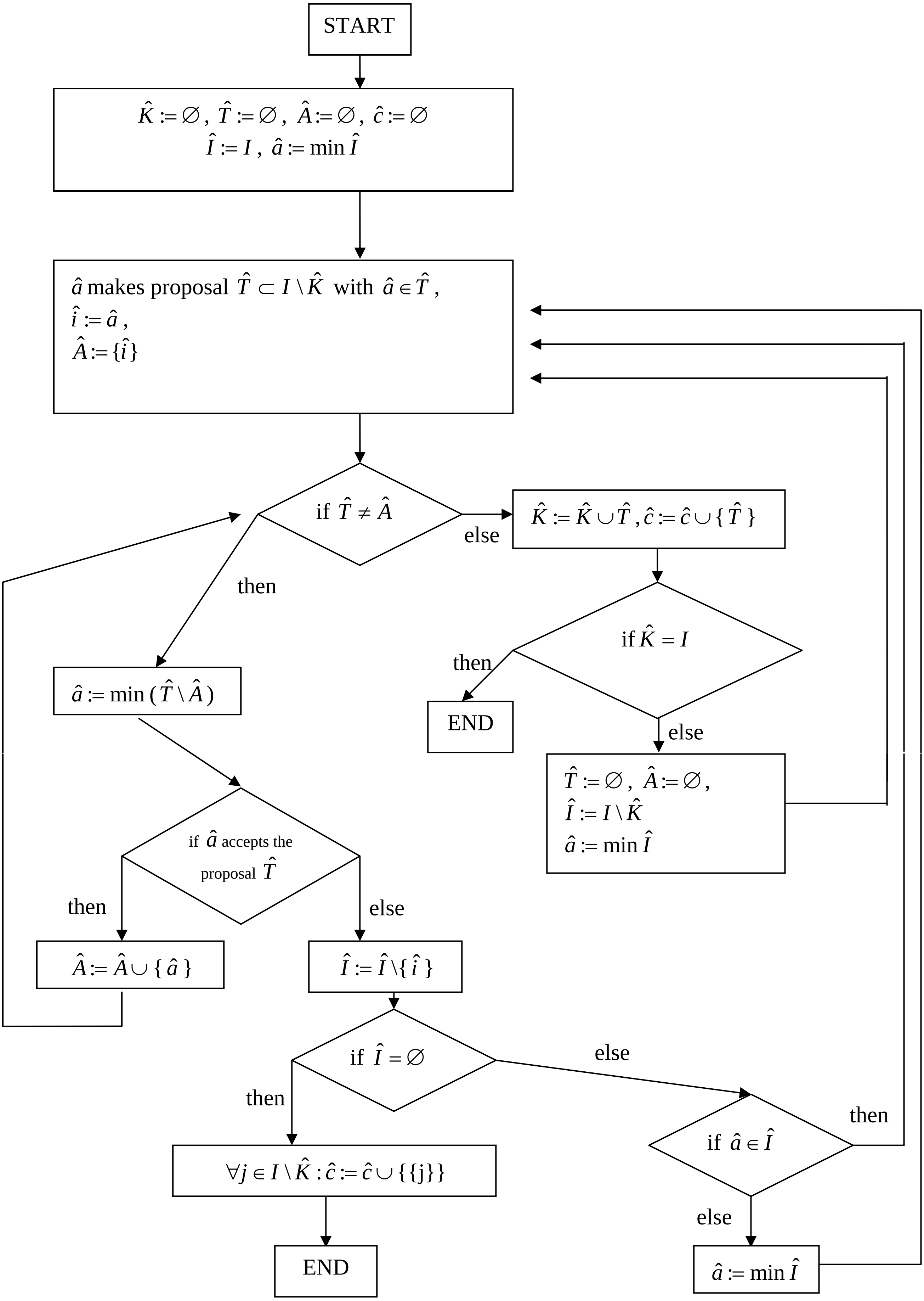
START
$\hat{K} := \varnothing$, $\hat{T} := \varnothing$, $\hat{A} := \varnothing$, $\hat{c} := \varnothing$
$\hat{I} := I$, $\hat{a} := \min \hat{I}$
$\hat{a}$ makes proposal $\hat{T} \subset I \setminus \hat{K}$ with $\hat{a} \in \hat{T}$,
$\hat{i} := \hat{a}$,
$\hat{A} := \{\hat{i}\}$
if $\hat{T} \neq \hat{A}$
else
then
$\hat{K} := \hat{K} \cup \hat{T}$, $\hat{c} := \hat{c} \cup \{\hat{T}\}$
if $\hat{K} = I$
then
END
else
$\hat{T} := \varnothing$, $\hat{A} := \varnothing$,
$\hat{I} := I \setminus \hat{K}$
$\hat{a} := \min \hat{I}$
$\hat{a} := \min(\hat{T} \setminus \hat{A})$
if $\hat{a}$ accepts the proposal $\hat{T}$
then
else
$\hat{A} := \hat{A} \cup \{\hat{a}\}$
$\hat{I} := \hat{I} \setminus \{\hat{i}\}$
if $\hat{I} = \varnothing$
then
else
$\forall j \in I \setminus \hat{K} : \hat{c} := \hat{c} \cup \{\{j\}\}$
END
if $\hat{a} \in \hat{I}$
then
else
$\hat{a} := \min \hat{I}$

Table 1: Overview of Selected Coalition Structures and their Welfare Implications*

Rank	Coalition Structure	Valuations without Transfers						Valuation with Transfers							
		USA	JPN	EU	CHN	FSU	ROW	USA	JPN	EU	CHN	FSU	ROW	World	CGX
1	{USA,JPN,EU,CHN,FSU,ROW}	255882.2	48068.1	179478.3	308069.3	19038.2	**359617.9**	257401.2	48116.1	179507.6	307220.6	19417.5	**358490.8**	1170154	100.0
2	{USA,EU,CHN,FSU,ROW},{JPN}	255793.3	**48435.0**	179368.4	307762.0	19041.8	359127.1	257267.1	48435	179408.9	306960.3	19408.5	358047.7	1169528	97.9
3	{USA,JPN,EU,CHN,ROW},{FSU}	255686.8	48029.6	179319.5	307610.7	**19622.1**	358882.0	257232.0	48085.9	179385.9	306892.3	**19622.1**	357932.4	1169151	96.7
4	{USA,EU,CHN,ROW},{JPN,FSU}	255613.6	48393.4	179229.2	307361.9	19603.1	358486.6	257119.4	**48448.9**	179306.9	306685.0	19547.6	357580.0	1168688	95.1
5	{USA,EU,CHN,ROW},{JPN},{FSU}	255590.1	48390.2	179212.7	307314.3	19604.3	358409.0	257095.3	48390.2	179289.9	306638.8	19604.3	357502.2	1168521	94.6
6	{USA,JPN,CHN,FSU,ROW},{EU}	255592.8	47979.2	**180526.1**	307021.0	19059.2	357931.3	256915.2	48029.0	**180526.1**	306307.3	19386.1	356945.9	1168110	93.2
16	{USA},{JPN,EU,CHN,FSU,ROW}	**258283.8**	47886.3	178712.9	305884.7	19045.5	356069.0	**258283.8**	47963.2	178896.8	305609.3	19362.1	355767.0	1165882	85.8
17	{USA,JPN,EU,FSU,ROW},{CHN}	255393.4	47872.6	178657.4	**308478.0**	19117.0	356225.0	256298.4	47919.5	178721.3	**308478.0**	19345.0	354980.3	1165743	85.4
150	{USA},{JPN},{EU},{CHN}, {FSU,ROW}	255723.7	47788.2	178265.1	304393.3	19155.1	352360.0	255723.7	47788.2	178265.1	304393.3	19289.5	352225.5	1157685	58.6
151	{USA},{JPN,ROW},{EU},{CHN}, {FSU}	255705.1	47660.4	178251.7	304362.0	19332.1	352195.0	255705.1	47759.9	178251.7	304362.0	19332.1	352095.5	1157506	58.1
152	{USA,JPN,EU,CHN,FSU},{ROW}	253310.9	47467.0	176958.1	300739.6	19016.4	350146.7	253718.4	47470.1	176907.2	300219.1	19177.1	350146.7	1147639	25.3
157	{USA,JPN,CHN,FSU,},{EU}, {ROW}	253151.6	47416.4	177134.2	300178.2	19037.5	348238.3	253464.8	47426.3	177134.2	299732.3	19160.4	348238.3	1145156	17.1
167	{USA},{JPN,EU,CHN,FSU}, {ROW}	253722.2	47376.6	176572.6	299713.5	19038.2	347037.4	253722.2	47405.3	176644.5	299498.8	19152.3	347037.4	1143461	11.5
173	{USA,JPN,EU,FSU},{CHN},{ROW}	253282	47396.9	176655.7	300001.6	19094.0	346569.3	253283.1	47394.9	176602.3	300001.6	19148.3	346569.3	1142999	9.9
195	{USA},{JPN,EU,FSU},{CHN},{ROW}	253219.5	47369.1	176534.5	299267.3	19120.0	345276.0	253219.5	47372.5	176511.4	299267.3	19139.7	345276.0	1140787	2.6
203	{USA},{JPN},{EU},{CHN},{FSU}, {ROW}	253104.6	47364.1	176477.5	299040.1	19136.5	344878.6	253104.6	47364.1	176477.5	299040.1	19136.5	344878.6	1140001	0.0

* Rank: rank of coalition structure in the list of all coalition structures sorted in descending order of global welfare (column “World”); valuations are billion US dollars expressed in 2000 levels, rounded to the first digit; World: sum of valuations of all six regions (i.e. global welfare); CGX: global welfare expressed in terms of closing the gap index: $100\cdot\left(\sum_{i=1}^{n}(v_i(c)-v_i(c^N))\right)/\left(\sum_{i=1}^{n}(v_i(c^F)-v_i(c^N))\right)$ where welfare is discounted lifetime consumption integrated over 2000-2300 (see section 3.1), global welfare with full cooperation is denoted by $\sum_{i=1}^{n}v_i(c^F)$ (c^F =coalition structure No. 1), global welfare with no cooperation is denoted by $\sum_{i=1}^{n}v_i(c^N)$ (c^N =coalition structure No. 203) and global welfare in some coalition structure c is denoted by $\sum_{i=1}^{n}v_i(c)$; abbreviation of regions as explained in the text in section 3.1; bold numbers indicate highest valuation of a region among the set of valuations $V(C)$ and $V^T(C)$, respectively.

Table 2: Equilibrium Coalition Structures for No Transfers and Transfers*

No Transfers										
Coalition Structure	Ranking							CGX	PO	FR
	USA	JPN	EU	CHN	FSU	ROW	World			
{USA,EU,FSU},{JPN},{CHN,ROW}	1	1	1	5	9	1	1	80.7	yes/yes	32
{USA,JPN,EU},{CHN,ROW},{FSU}	3	3	3	6	1	2	2	80.3	yes/yes	52
{USA,EU},{JPN},{CHN,ROW},{FSU}	5	2	4	8	2	3	3	78.2	yes/yes	515
{USA,JPN,FSU},{EU},{CHN,ROW}	2	5	2	9	5	4	4	76.2	yes/yes	1
{USA},{JPN},{EU,FSU},{CHN,ROW}	4	4	5	10	4	9	5	73.7	no/no	16
{USA},{JPN,EU},{CHN,ROW},{FSU}	6	6	6	11	3	10	6	73.4	no/no	4
{USA,ROW},{JPN},{EU,FSU},{CHN}	8	7	7	1	10	5	7	72.2	no/yes	8
{USA,ROW},{JPN,EU},{CHN},{FSU}	9	10	8	2	6	6	8	71.9	no/yes	10
{USA,ROW},{JPN,FSU},{EU},{CHN}	10	8	9	3	8	7	9	71.3	no/yes	2
{USA,ROW},{JPN},{EU},{CHN},{FSU}	11	9	10	4	7	8	10	70.8	no/yes	78
{USA},{JPN},{EU,ROW},{CHN},{FSU}	7	11	11	7	11	11	11	63.8	no/no	2
								$\varnothing = 77.3$		
Transfers										
Coalition Structure	Ranking							CGX	PO	FR
	USA	JPN	EU	CHN	FSU	ROW	World			
{USA,EU,CHN,ROW},{JPN},{FSU}	2	1	1	1	1	1	1	94.6	yes/yes	706
{USA},{JPN},{EU,FSU},{CHN,ROW}	1	2	2	2	2	2	2	73.7	no/yes	14
								$\varnothing = 94.2$		

* Ranking: ranking of equilibrium coalition structures in terms of valuations "World" in descending order; CGX: closing the gap index as explained in Table 1, $\varnothing$ =average welfare over all possible index sequences; PO: first entry = Pareto-optimal coalition structure in the set of all coalition structures, second entry = Pareto-optimal coalition structure in the set of equilibria; FR: frequence of appearance of coalition structure as an equilibrium out of the total number of index sequences that is 720.

Table 3: First-Mover Advantage to Enforce Best and to Avoid Worst Equilibrium*

No Transfers						
	USA	JPN	EU	CHN	FSU	ROW
Best Equilibrium	**93.8**	43.8	18.8	**100**	**73.1**	18.8
Worst Equilibrium	**15.4**	100	**0**	50	**0**	**0**
Transfers						
	USA	JPN	EU	CHN	FSU	ROW
Best Equilibrium	**100**	**50.4**	**50.1**	49.3	**50.1**	**51**
Worst Equilibrium	**49**	**28.6**	**42.9**	85.7	**42.9**	**0**

* Numbers are percentages of region i having an index number equal or smaller than 3 with respect to the the best and worst equilibrium coalition structure from player i's perspective in Table 2. Bold entries: %>50 for Best Equilibrium and %<50 for Worst Equilibrium indicate first-mover advantage.