Cartel Stability under an Optimal Sharing Rule

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Summary

Previous work on the formation and stability of cartels has focused on the case of identical players. This assumption is very restrictive in many economic environments. This paper analyses stability of cartels in games with heterogeneous players and spillovers to non-members. I introduce a sharing rule for coalition payoffs, called "optimal sharing" which stabilises all cartels that are possibly stable under any rule. Under optimal sharing the grand coalition is the unique stable cartel if spillovers are negative. I introduce a new property, called "non-essentiality" and determine the set of stable cartels under optimal sharing if spillovers are positive and if the non-essentiality property applies. Finally I analyse cartel stability under optimal sharing in simple public goods game with heterogeneous players. My results show – in contrast to earlier findings for identical players – that large coalitions may well be stable.

Keywords: Cartel stability, Coalition formation games with spillovers, Partition function approach, Optimal sharing rule

JEL Classification: C72, D72, H41

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1 Introduction

Recent work on the formation and stability of coalitions has focused on the partition function approach. A partition function is a generalisation of the characteristic function of a coalition formation game introduced by von Neumann and Morgenstern (1944). The characteristic function assigns a payoff to each coalition which is independent of the actions taken by non-members. In many economic environments this assumption is too restrictive. The partition function approach, first introduced by Thrall and Lucas (1963), relaxes this assumption. The coalition payoff may depend on the entire coalition structure. This allows to consider spillovers, that is, the formation of a coalition affects the payoffs of non-members. Because coalition payoffs are insufficient to identify (Nash) equilibria of coalition formation games, Bloch (1996), Yi (1997), and Ray and Vohra (1999) have introduced a *per-member partition function*. Findings have been surveyed by Bloch (2003) and Yi (2003). The move from coalition payoffs to individual payoffs requires the use of a sharing rule. In their coalition formation models Bloch (1996), Yi (1997) and Ray and Vohra (1999) assume identical players and equal sharing of coalition payoffs. In this paper I relax this symmetry assumption. In a more general setting, with differences in players' characteristics, equal sharing is less convincing. I introduce an alternative sharing rule and apply it to a cartel formation game. The sharing rule suggested here distributes the coalition payoff proportional to outside-option payoffs. It can be shown that if a coalition is internally stable under some sharing rule, then it is internally stable under the suggested rule.[1] I will refer to this rule as "optimal sharing". Optimal sharing will guarantee internal stability whenever it is at all feasible.

The approach in this paper is more general than the existing literature because it relaxes the identical players assumption. The generality with respect to players' characteristics comes at some cost. I consider only cartel formation games in which it is assumed that at most one non-trivial coalition might form. The analysis focuses on internal and external stability of cartels. A cartel is stable when no member has an incentive to leave and no non-member has an incentive to join.

Two main results are obtained. Both results require a superadditive payoff function. In other words, a coalition can achieve at least as much as its members can achieve individually. First, I consider the case of negative spillovers where non-members lose when others form a coalition. I prove that the grand coalition is the unique stable cartel under optimal sharing. Second, for the case of positive spillovers where non-members gain when others form a coalition, I show that the set of stable cartels can be generated by a simple algorithm, provided the payoff function satisfies a "non-essential player" property. A player is non-essential in an internally stable coalition if the remaining coalition without that player is internally stable. The intuition behind my result is that every stable coalition can be "built up"

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[1] Internal stability means that no coalition member has an incentive to leave.

stepwise by a sequence of internally stable enlargements starting from a small internally stable coalition. If the non-essential player property does not hold, that is, if all players of a coalition are essential, then this coalition cannot be built up by a sequence of internally stable enlargements. In such case the set of stable cartels is almost unrestricted.

A cartel formation game with positive spillovers has first been introduced by d'Aspremont *et. al.* (1983). It has more recently received much attention in the study of international environmental agreements. These have been studied, for instance, by Barrett (1994) and Hoel and Schneider (1997). The applicability of cartel formation games, however, has so far been hampered by the restrictive assumption of identical players. In a cartel formation game a player's strategy set consists of the options whether or not to become a coalition member. The payoffs of all players (not only coalition members' payoffs) depend on the coalition formed. There are spillovers to non-members. A typical situation where such game structure arises is the provision of public goods. It is well-known from the literature on private provision of public goods that – due to free-riding – inefficiently low levels of public goods are provided, since players do not take others' benefits into account. The inefficiency problem may be mitigated to some extent if we allow for coalition formation. Barrett (1994, p. 891) concludes from the analysis of a symmetric cartel game that self-enforcing agreements (coalitions) "may not be able to improve substantially upon the non-cooperative outcome." An additional finding in this paper is that Barrett's result does not generalise to cases where players differ with respect to their marginal benefits of the public good. In fact, any coalition can be stable if one player's marginal benefit is sufficiently large.

The next section introduces a cartel formation game. Section 3 introduces the sharing rule and shows that it "maximises" stability. Section 4 contains the main results of the paper. The characterisation of stable coalitions in cartel formation games with heterogeneous players is a major contribution to coalition theory and will stimulate new applied work in, for instance, industrial economics, environmental economics, and public choice. Section 5 provides an application. I show for a simple public goods game with non-identical players that it has the non-essential player property and, hence, the set of stable cartels is easy to compute. Section 6 concludes.

2 The cartel game

Let N be a finite set of players. Players are denoted by i, j and so on. Each player j chooses a strategy $\sigma_j \in \{0,1\}$. If player j chooses $\sigma_j = 1$, she will be a member of a (unique) coalition; if she chooses $\sigma_j = 0$, she will not be a member. Let $C \subseteq N$ be the set of coalition members. Suppose $i \in C$, then C_{-i} is the shorthand notation for coalition $C \setminus \{i\}$, *i.e.* the remaining coalition when i "leaves". Similarly, C_{+j} is the shorthand for $C \cup \{j\}$; $j \notin C$. $\pi_i(C)$ is the payoff of player i under coalition C. $\pi_i(C_{-i})$ is i's outside option payoff which I will also call her claim. For convenience, I assume that $\pi_j(C) \geq 0$ for all $j \in N$ and all $C \subseteq N$. Furthermore, I assume that for all $i, j \in N$, $\pi_j(\{i\}) = \pi_j(\varnothing)$. If only a single player announces "1", the (trivial) coalition formed is not effective.

It is obvious that the sharing rule applied to distribute the coalition payoff will affect the stability of a coalition, that is, the incentives to join or stay out. Individual payoffs of members of coalition C are derived from the joint coalition payoff $\pi(C)$ by applying a sharing rule. A sharing rule $\mathcal{R}$ distributes the coalition payoff. It assigns a payoff π_i to each coalition member *i*. Formally, for every coalition $C \in 2^N$ and every sharing rule $\mathcal{R}: 2^N \rightarrow \mathbb{R}^{|C|}$, $\mathcal{R}(C) = (\pi_i)_{i \in C}$ and $\sum_{i \in C} \pi_i(C) = \pi(C)$.

We now define the concepts of internal and external stability. The condition for internal stability is that each coalition member gets at least as much as she gets when leaving the coalition, while others stay on. External stability means that no player outside the coalition would gain by joining the coalition. Denote the set of internally stable coalitions by $\widehat{S}$, and the set of externally stable coalitions by $\breve{S}$. Formally:

DEFINITION 1 (internal stability): $C \in \widehat{S}$ if and only if for all $i \in C$ it holds that

$$\pi_i(C) \geq \pi_i(C_{-i}). \tag{1}$$

DEFINITION 2 (external stability): $C \in \breve{S}$ if and only if for all $j \in N \setminus C$ it holds that

$$\pi_j(C) > \pi_j(C_{+j}).^{2} \tag{2}$$

Coalition *C* is called a stable coalition if and only if it is internally and externally stable. The set of stable coalitions is denoted by *S*.

DEFINITION 3 (stability): $C \in S$ if and only if $C \in \widehat{S} \cap \breve{S}$.

Clearly, if (1) and (2) hold, we have a Nash equilibrium of the cartel formation game as no player has an incentive to deviate from her chosen strategy. The set of stable coalitions *S* is a subset of all Nash equilibria. The full set is obtained if we weaken the stability definition and replace the strict inequality sign in (2) by a weak inequality sign. In the remainder of the paper I will use the stronger stability notion of definitions 1-3.

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[2] The tie-breaking rule is here that a player would join the coalition if she is indifferent between joining and staying out. Hence, by this definition, the empty set $\varnothing$ is not externally stable, and a trivial coalition is internally stable.

3 Optimal sharing rules

Consider the following class of sharing rules $\mathcal{R}^o$ where each coalition member receives her outside option payoff $\pi_i(C_{-i})$ and the residual $\pi(C)-\sum_{i\in C}\pi_i(C_{-i})$ is shared in an arbitrary way. Formally this class of sharing rules is charcterised by the following condition.

> *Weak Equal Treatment Condition:* For all $i \in C$ and all $C \subseteq N$, $\pi_i(C) \geq \pi_i(C_{-i})$ if and only if $\pi(C) \geq \sum_{i\in C}\pi_i(C_{-i})$.

Of all possible sharing rules the Weak Equal Treatment Condition selects the class of surplus sharing rules where outside option payoffs define an "original position".[3]

A particular sharing rule belonging to the class $\mathcal{R}^o$ is sharing proportional to outside option payoffs, $\mathcal{R}^*$. For all $i \in C$

$$\pi_i(C) = \alpha(C)\pi_i(C_{-i}), \tag{3}$$

where $\alpha(C) = \dfrac{\pi(C)}{\sum_{i\in C}\pi_i(C_{-i})}$.

The results that follow in the remainder of the paper are derived for $\mathcal{R}^*$, but they hold for every rule in $\mathcal{R}^o$ as the incentives to join or leave a coalition do not depend on the distribution of the residual $\pi_i(C)-\sum_{i\in C}\pi_i(C_{-i})$.[4]

It can be shown that $\mathcal{R}^*$ produces the largest possible set of internally stable coalitions.

> THEOREM 1 In a cartel formation game, if coalition *C* is not internally stable under sharing rule $\mathcal{R}^*$, then *C* is not internally stable under any rule.

Proof: Internal stability requires by definition that for all $i \in C$, $\pi_i(C) \geq \pi_i(C_{-i})$. It follows that the coalition must earn at least the sum of the outside option payments

$$\sum_{i\in C}\pi_i(C) \geq \sum_{i\in C}\pi_i(C_{-i}). \tag{4}$$

If (4) holds, then $\alpha \geq 1$ and

$$\pi(C) = \alpha(C)\sum_{i\in C}\pi_i(C_{-i}) \geq \sum_{i\in C}\pi_i(C_{-i}).$$

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[3] The Weak Equal Treatment Condition is usually violated in applied studies on coalition stability. Cf. e.g. Weikard et al. (2004) and the references cited therein.

[4] Note that $\mathcal{R}^*$ is the equal sharing rule for identical players.

According to $\mathcal{R}^*$, for all $i \in C$, $\pi_i(C) = \alpha(C)\pi_i(C_{-i})$. If *C* is unstable under $\mathcal{R}^*$, then there exists $i \in C$ such that $\pi_i(C) < \pi_i(C_{-i}) \Leftrightarrow \alpha(C)\pi_i(C_{-i}) < \pi_i(C_{-i})$. Hence, $\alpha(C) < 1$, and the coalition payoff is less than the sum of the outside option payments. This violates the necessary condition for internal stability (4). Therefore, there cannot exist a sharing rule under which *C* is internally stable if *C* is internally unstable under $\mathcal{R}^*$. QED.

Theorem 1 says that if *C* is stable under some sharing rule, then *C* is stable under $\mathcal{R}^*$. This allows us to focus further analysis of coalition stability on rule $\mathcal{R}^*$ and still be sure that no internally stable coalition escapes our attention. Other possible sharing rules need not be considered because no rule can generate an internally stable coalition that is not also internally stable under $\mathcal{R}^*$.

The following Lemma sheds light on the relationship between coalitions *C* and C_{+j}.

> LEMMA 1 In a cartel formation game, under sharing rule $\mathcal{R}^*$, coalition *C* is externally unstable if and only if, there exists $j \in N \setminus C$ such that C_{+j} is internally stable.

Proof: Suppose *C* is externally unstable, then there exists $j \in N \setminus C$ such that $\pi_j(C) \le \pi_j(C_{+j})$. Note now that $\pi_j(C)$ is *j*'s outside option payoff with respect to coalition C_{+j}. Under $\mathcal{R}^*$, if $\pi_j(C_{+j}) \ge \pi_j(C)$ holds for j, then $\pi_i(C_{+j}) \ge \pi_i(C_{+j-i})$ for all $i \in C \cup \{j\}$. Every member of the enlarged coalition $C \cup \{j\}$ receives at least her outside option payoff and, hence, the enlarged coalition is internally stable. QED.

Lemma 1 implies that every coalition *C* is either externally stable or there exists an enlarged coalition C_{+j} which is internally stable. This characteristic will be helpful for identifying the set of stable coalitions.

4 Cartel stability

For what follows I impose restrictions on the payoffs. First, payoffs are required to be superadditive. A coalition *C* joined by an additional member *j* can achieve at least as much as *C* and *j* can achieve independently.

> DEFINITION 4 (superadditivity): Payoffs are superadditive if and only if for all coalitions $C \subset N$ and all $j \in N \setminus C$, it holds that $\pi(C_{+j}) \ge \pi(C) + \pi_j(C)$.

Superadditivity is a natural assumption as all options open to a set of individual players should be open to a team. The following holds:

> LEMMA 2 In a cartel formation game, under sharing rule $\mathcal{R}^*$, if payoffs are superadditive, then every two-player coalition is internally stable.

Proof: Consider $C=\{i\}$. It follows from superadditivity that $\pi(\{i,j\})\geq\pi(\{i\})+\pi_j(\{i\})$. Since, for all i, $\pi(\{i\})=\pi_i(\{j\})=\pi_i(\varnothing)$, the superadditivity property can be rewritten as $\pi(\{i,j\})\geq\pi_i(\{j\})+\pi_j(\{i\})$. This says that the coalition payoff is at least as much as the sum of the outside option payoffs. Hence, under $\mathcal{R}^*$ every player receives at least her outside option payoff and, hence, all two-player coalitions are internally stable. QED.

In what follows I call C_{+j}, where $j\in N\setminus C$, an *internally stable enlargement* of *C* if both, *C* and C_{+j}, are internally stable.

> THEOREM 2 A non-trivial ($|C|\geq 2$) stable coalition always exists in a cartel formation game, under sharing rule $\mathcal{R}^*$, if payoffs are superadditive.

Proof: The proof is by contradiction. Suppose no non-trivial stable coalition exists. By Lemma 2 all two-player coalitions *C* are internally stable. By assumption they are unstable. Hence, they must be externally unstable. Then, by Lemma 1, there exists an internally stable enlargement C_{+j}. Again, by assumption C_{+j} is not stable and, hence, not externally stable. Then, Lemma 1 applies again, and so on. Then there must be a sequence of internally stable enlargements. If an enlarged internally stable coalition reaches size *N*, there cannot be a further enlargement. Hence, a stable coalition *C* must exist such that $2\leq|C|\leq|N|$. QED.

The next restriction I impose concerns spillovers. I will examine two cases: negative spillovers and positive spillovers. With negative spillovers non-members lose as the coalition grows. In this case the grand coalition ($C=N$) is stable. Note that under superadditivity, the grand coalition is always efficient. In the case of positive spillovers, non-members gain when others join the coalition. Here the issue is more complex. Usually an efficient outcome (the grand coalition) cannot be obtained as there are strong free rider incentives. An examples is discussed in section 5. The simpler case of negative spillovers is discussed in turn.

> DEFINITION 5 (negative spillovers): Payoffs exhibit negative spillovers if and only if for all coalitions $C\subset N$ and all $j,k\in N\setminus C$ it holds that $\pi_j(C_{+k})<\pi_j(C)$.

The following theorem holds.

> THEOREM 3 In a cartel formation game, under sharing rule $\mathcal{R}^*$, if payoffs are superadditive and exhibit negative spillovers, then the grand coalition is the unique stable coalition: $S=\{N\}$.

Proof: The proof is by induction. There are three steps. First, we show that if a coalition *C* is internally stable, then C_{+j} is also internally stable.

Step 1: Suppose *C* is internally stable. Then, under $\mathcal{R}^*$, everyone receives more than her claim, as $\pi(C)\geq\sum_{i\in C}\pi_i(C_{-i})$. By superadditivity $\sum_{i\in C}\pi_i(C_{+j})+\pi_j(C_{+j})\geq\sum_{i\in C}\pi_i(C)+\pi_j(C)$. Then, it also holds that $\sum_{i\in C}\pi_i(C_{+j})+\pi_j(C_{+j})\geq\sum_{i\in C}\pi_i(C_{-i})+\pi_j(C)$. Note now that the sum of the claims of coalition C_{+j} is $\sum_{i\in C}\pi_i(C_{+j-i})+\pi_j(C)$. By negative spillovers we have $\sum_{i\in C}\pi_i(C_{+j-i})<\sum_{i\in C}\pi_i(C_{-i})$. Hence, $\sum_{i\in C}\pi_i(C_{+j})+\pi_j(C_{+j})\geq\sum_{i\in C}\pi_i(C_{-i})+\pi_j(C)>\sum_{i\in C}\pi_i(C_{+j-i})+\pi_j(C)$. This establishes that the payoff of coalition C_{+j} is larger than the sum of the claims of the coalition members. We conclude that if coalition C is internally stable, then C_{+j} is internally stable.

Step 2: By Lemma 2 we know that an internally stable two-player coalition exists. By step 1 we know that every enlargement of a n-player coalition to an n+1-player coalition generates an internally stable coalition. Hence, all coalitions are internally stable.

Step 3: By Lemma 1, if, there exists $j\in N\setminus C$ such that $C\cup\{j\}$ is internally stable, then C is externally unstable. Such j always exists unless C is the grand coalition. Hence, the grand coalition is the unique stable coalition. QED.

We now turn to the more interesting case of positive spillovers. Positive spillovers imply that there are free rider incentives. Thus, we expect stable coalitions that are smaller than the grand coalition, but according to Lemma 2 stable coalitions have at least two members.

> DEFINITION 6 (positive spillovers): Payoffs exhibit positive spillovers, if and only if for all coalitions $C\subset N$ and all $j,k\in N\setminus C$ it holds that $\pi_j(C_{+k})\geq\pi_j(C)$.

While superadditive payoffs give an incentive to join the coalition, positive spillovers work in the opposite direction. A larger coalition does not only achieve more for its members but it also generates larger benefits to non-members. These benefits are an obstacle to forming large and successful coalitions. Generally, superadditivity and positive spillovers do not limit the set of possible stable coalitions. If free rider incentives are very strong, the set of stable coalitions may just be the set of two-player coalitions. If, however, only the grand coalition achieves a substantial gain while smaller coalitions are largely ineffective, then the grand coalition may be in the set of stable coalitions. One constraint on the set of stable coalitions is that if C is stable no subset of C of size $|C|-1$ is stable. The following Lemma holds.

> LEMMA 3 In a cartel formation game, under sharing rule $\mathcal{R}^*$, if $C\in S$, then $C_{-i}\notin S$.

Proof: If $C\in S$, then by definition of stability C is internally stable. From Lemma 1 we know that if C is internally stable then C_{-i} is not externally stable. Hence, $C_{-i}\notin S$. QED.

Without further restrictions on the payoff structure, there is little more to say. However, we can identify a class of cartel formation games for which all stable coalitions can be generated in a simple straightforward manner. This class of games is characterised by the fact that *not all* players are essential for the success of the coalition. A player is essential if, without this player, the remaining coalition is internally unstable and would fall apart. I formally define the property of non-essentiality. A lemma follows.

> DEFINITION 7 (non-essentiality): Player $i \in C$ is non-essential for coalition $C \in \widehat{S}$ if and only if $C_{-i} \in \widehat{S}$.

> LEMMA 4 In a cartel formation game with superadditivity, under sharing rule $\mathcal{R}^*$, if every internally stable coalition has a non-essential member, then there exists a sequence of internally stable enlargements from $|C| = 2$ for every stable coalition.

Proof: We assume that every internally stable coalition has a non-essential member. Consider a stable coalition C of size $|C| = n > 2$. As C is stable, it is also internally stable and has a non-essential member. Hence, there exists a coalition $C_{-i} \in \widehat{S}$ of size $n-1$. As $C_{-i} \in \widehat{S}$, there exists $C_{-i-j} \in \widehat{S}$, and so forth until the size of the coalition is 2. This establishes the result. QED.

The existence of a non-essential player rules out payoff structures with specific synergies. Consider a large stone that can only be moved by four persons. Any three would not be strong enough to do so. In this case, a coalition of four could be stable, while there is no internally stable coalition of three. The existence of a non-essential member in every internally stable coalition rules out the possibility of stable coalitions of size $n+1$ if there does not exist an internally stable coalition of size n.

I call a *sequence of internally stable enlargements* leading to C "*complete*" if C can be described by a sequence of internally stable enlargements and if there is no $j \in N \setminus C$ such that C_{+j} is internally stable. I can show now that the set of complete sequences of internally stable enlargements coincides with the set of stable coalitions.

> THEOREM 4: In a cartel formation game with superadditivity, under sharing rule $\mathcal{R}^*$, if every internally stable coalition has a non-essential member, then the set of complete sequences of internally stable enlargements coincides with the set of stable coalitions.

Proof: First, notice that a complete sequence of internally stable enlargements leads to a stable coalition: If C is generated by a sequence of internally stable enlargements, then it is, by definition, internally stable. As the sequence is complete there does not exist $j \in N \setminus C$ such that C_{+j} is internally stable. Then, by Lemma 1, C is externally stable and, hence, stable.

Second, Lemma 4 establishes that every stable coalition can be constructed by a sequence of internally stable enlargements. This sequence is in fact a complete sequence, since, by Lemma 1, there cannot be an internally stable enlargement. Hence, the set of complete sequences of internally stable enlargements coincides with the set of stable coalitions. QED.

Note that the converse of Theorem 4 is not true. The set of complete sequences of internally stable enlargements may coincide with the set of stable coalitions while there exist internally stable coalitions consisting of essential members only.

The importance of Theorem 4 is that it identifies a class of coalition formation games for which the set of stable coalitions is easy to compute. It is easy to establish a simple algorithm that generates the stable coalitions for the class of cartel formation games with non-essential members in every internally stable coalition.

> DEFINITION 8 (simple algorithm): (i) Start with $n = 2$. (ii) Check each internally stable n-player coalition C for internally stable enlargements for all $j \in N \setminus C$. If there is no internally stable enlargement of C, then the sequence is complete. If there is an internally stable enlargement C_{+j}, put it on a list of internally stable coalitions of size $n+1$. (iii) If the check is completed, proceed with the listed internally stable $n+1$-player coalitions at step (ii). (iv) Stop when the list of internally stable $n+1$-player coalitions is empty.

The following holds.

> THEOREM 5 The simple algorithm generates the stable coalitions in a cartel formation game with superadditivity, under sharing rule $\mathcal{R}^*$, if every internally stable coalition has a non-essential member.

Proof: By construction the simple algorithm generates all complete sequences of internally stable enlargements. Theorem 4 establishes that the set of complete sequences of internally stable enlargements coincides with the set of stable coalitions. QED.

5 Cartel formation and the provision of public goods

In this section I show that Theorems 4 and 5 have important applications. I consider the case of the provision of public goods when benefits are linear and costs are quadratic. More specifically, I consider the two-stage game introduced by d'Aspremont et al. (1983) and applied to public goods problems by Barrett (1994), Chander and Tulkens (1995), Carraro and Marchiori (2003) and others in more recent years. The important difference is that here I relax the identical players assumption usually invoked in the literature and I apply the optimal sharing rule developed in this paper. There are N players. At stage 1 each player considers whether or not to join a binding agreement. Those who join, coalition C, fully cooperate in the provision of the public good at the second stage. They maximise the coalition payoff and share the payoff according to $\mathcal{R}^*$. The remaining players $N \setminus C$, the free riders, maximise their individual payoffs.

I show that this game satisfies the condition that there exists a non-essential player for every internally stable coalition. Accordingly, all stable coalitions can be computed by the simple algorithm.

Let $b_i \geq 0$ denote individual marginal benefits, $a_i \geq 0$ denotes a cost parameter, and z_i denotes the amount of public good provided by *i*. The total amount provided is $z = \sum_{i \in N} z_i$.

At stage 2 of the game a free rider $k \notin C$ maximises:

$$\pi_k(C) = b_k z_k + b_k \sum_{j \in N \setminus \{k\}} z_j - \tfrac{1}{2} a_k z_k^2 . \tag{5}$$

It follows from a free rider's first order condition that

$$z_k^* = \frac{b_k}{a_k} . \tag{6}$$

The coalition maximises the joint payoff which is then available for distribution,

$$\pi(C) = \sum_{i \in C} b_i \sum_{k \in N} z_k - \sum_{i \in C} \tfrac{1}{2} a_i z_i^2 . \tag{7}$$

From the set of first order conditions we have

$$z_i^* = \frac{\sum_{j \in C} b_j}{a_i} . \tag{8}$$

for all $i \in C$ (Samuelson's rule).

Given the first order conditions the equilibrium coalition payoff is:

$$\pi(C) = \sum_{i \in C} \left(b_i \sum_{j \in C} \frac{\sum_{k \in C} b_k}{a_j} + b_i \sum_{l \notin C} \frac{b_l}{a_l} - \sum_{i \in C} \tfrac{1}{2} \frac{\left(\sum_{k \in C} b_k \right)^2}{a_i} \right) . \tag{9}$$

When we do not consider redistribution, the term in brackets is the individual net benefit for coalition member *i*. The first addend in the bracket is the benefit from the public good provided by coalition members; the second addend gives the benefit from the provision by free riders: the third addend is *i*'s cost of optimal provision.

A coalition *C* applying $\mathcal{R}^*$ will be internally stable if and only if the coalition payoff (9) is at least as much as the sum of the claims of the coalition members. Recall that player *i*'s claim is the payoff *i* would receive under coalition C_{-i}. Recall also that $\mathcal{R}^*$ divides the coalition payoff proportional to claims. Player *i*'s claim ($i \in C$) is given by

$$\pi_i(C_{-i}) = b_i\frac{b_i}{a_i} + b_i\sum_{j\in C_{-i}}\frac{\sum_{k\in C_{-i}} b_k}{a_j} + b_i\sum_{l\notin C}\frac{b_l}{a_l} - \tfrac{1}{2}\frac{b_i^2}{a_i}\,. \tag{10}$$

In order to check for internal stability, we have to compare (9) and the sum of individual claims $\sum_{i\in C}\pi_i(C_{-i})$. To simplify notation, let $\Phi(C)\equiv\sum_{i\in C}\pi_i(C_{-i})$.

Then, internal stability requires.

$$\pi(C)\geq\Phi(C)\,. \tag{11}$$

First, note that the following holds (see also Barrett's (1994) proposition 2).

> PROPOSITION 1 In a simple public goods game with linear benefits functions and quadratic costs functions, if players are identical ($a_i = a_j$ and $b_i = b_j$ for all $i, j\in N$), then every coalition of size 3 is stable.

Proof: To show that internal stability is satisfied, we first show that $\pi(C)-\Phi(C)=0$ for $|C|=3$. From (9) and (10) we obtain

$$\pi(C)-\Phi(C) = -\tfrac{1}{2}\left(\sum_{i\in C}b_i\right)^2\sum_{i\in C}\frac{1}{a_i} - \tfrac{3}{2}\sum_{i\in C}\frac{b_i^2}{a_i} + \sum_{i\in C}b_i\sum_{i\in C}\frac{b_i}{a_i} + \sum_{i\in C}b_i^2\sum_{i\in C}\frac{1}{a_i}\,. \tag{12}$$

Setting $a_i = a$, $b_i = b$, and $|C|=3$, we obtain from (12) that $\pi(C)-\Phi(C)=0$.

External stability is satisfied for $|C|=3$ for identical players because any 4-player coalition is internally unstable. Setting $a_i = a$, $b_i = b$, and $|C|=4$, we obtain from (12) that $\pi(C)-\Phi(C) = -6b^2/a<0$. QED.

In order to demonstrate that a public goods game with heterogeneous players has a non-essential member in every internally stable coalition, one has to show that if C is internally stable, then there exists i such that C_{-i} is internally stable.

The following proposition holds.

> PROPOSITION 2 In a simple public goods game with linear benefits functions ($b_i \geq 0$, for all $i\in N$) and quadratic costs functions ($a_i = 1$, for all $i\in N$), every internally stable coalition has a non-essential member.

Proof: The proof is given in the appendix.

Theorems 4 and 5 have established how the set of stable coalitions can be determined for any numerical specification.

Another important result follows easily. Barrett (1994) shows that only small coalitions will be stable in public goods games. But this result is obtained from a model with identical players. If we allow for heterogeneous players, as is the case here, large coalitions may well be stable. It is easy to construct examples with large numbers of players with different marginal benefits where the grand coalition is stable.

> PROPOSITION 3 In a simple public goods game with linear benefits functions and quadratic costs functions, where marginal benefits b_i and the cost parameter a_i are given for all $i \in N \setminus \{j\}$, the grand coalition is stable if player *j*'s marginal benefit is sufficiently large.

Proof: The proof is given in the appendix.

6 Conclusions

The study of coalition formation is burdened by the complexity of the strategic situation. In order to get a grip on the problem, theoretical models have assumed that players are identical. The identical players assumption has so far seriously limited the empirical relevance of coalition theory. This paper takes a few steps to overcome some of the difficulties in cartel formation games. The optimal sharing rule introduced in this paper guarantees that a coalition will in fact be internally stable, whenever it is at all possible to stabilise the coalition. I show that, under optimal sharing, the grand coalition is the unique stable cartel in games with negative spillovers. Furthermore, I identify a class of games with positive spillovers where stable cartels can be easily computed – even for games with many players. Furthermore, I find that Barrett's (1994) often quoted result that only small cartels are stable does not hold in a generalised class of games with heterogeneous players.

My results in this paper are important for applied work, for instance, for the study of international environmental agreements, trade regulations, R&D cooperation, and the classic topic of cartel formation in industries. The relaxation of the identical players assumption will give new impulses for further research in these and other areas.

Appendix

Proof of Proposition 2: We prove that every internally stable coalition in a simple public goods game with linear benefits functions and quadratic costs functions has a non-essential member. We have to show that

$$\text{if } C \text{ is internally stable, then there exists } j \in C \text{ such that } C_{-j} \text{ is internally stable.} \quad (*)$$

Notice first that (*) is satisfied for every C if $|C| \leq 3$ (cf. Lemma 2). For the remainder of the proof we assume that $|N| \geq |C| \geq 4$. Suppose C is internally stable. Then, the coalition payoff is at least as much as the sum of the claims. Internal stability requires $\pi(C) \geq \Phi(C)$. Under sharing rule $\mathcal{R}^*$ every player $i \in C$ receives $\alpha(C) \cdot \pi_i(C_{-i})$. Recall that $\alpha(C) \equiv \pi(C)/\Phi(C)$ and C is internally stable if and only if $\alpha(C) \geq 1$. We have to show that a non-essential member *j* exists in every internally stable coalition such that $\alpha(C_{-j}) \geq 1$ and, hence,

$$\pi(C_{-j}) - \Phi(C_{-j}) \geq 0 . \tag{A1}$$

To simplify notation denote $n \equiv |C|$. Assuming $a_i = 1$ for all $i \in N$ and internal stability of *C* we obtain from (12)

$$\pi(C) - \Phi(C) = -\frac{n-2}{2}\left(\sum_{i \in C} b_i\right)^2 + \frac{2n-3}{2}\sum_{i \in C} b_i^2 \geq 0 . \tag{A2}$$

This can be rewritten as

$$\frac{n-1}{2} b_j^2 - (n-2)\sum_{i \in C_{-j}} b_i b_j + \frac{2n-3}{2}\sum_{i \in C_{-j}} b_i^2 - \frac{n-2}{2}\left(\sum_{i \in C_{-j}} b_i\right)^2 \geq 0 . \tag{A3}$$

Furthermore, (A1) can be written as

$$-\left(\sum_{i \in C_{-j}} b_i\right)^2 + \frac{2n-5}{n-3}\sum_{i \in C_{-j}} b_i^2 \geq 0 . \tag{A4}$$

By appropriate manipulation of (A3) we obtain

$$-\left(\sum_{i \in C_{-j}} b_i\right)^2 + \frac{2n-5}{n-3}\sum_{i \in C_{-j}} b_i^2 - \frac{1}{(n-3)(n-2)}\sum_{i \in C_{-j}} b_i^2 - 2\sum_{i \in C_{-j}} b_i b_j + \frac{n-1}{n-2} b_j^2 \geq 0 . \tag{A5}$$

(A5) holds by assumption of internal stability of *C*. The first two addends of (A5) are equivalent to the condition for internal stability of C_{-j}. This is clear from (A4). We denote the last three addends of (A5) by

$$\Omega \equiv -\frac{1}{(n-3)(n-2)}\sum_{i \in C_{-j}} b_i^2 - 2\sum_{i \in C_{-j}} b_i b_j + \frac{n-1}{n-2} b_j^2 . \tag{A6}$$

Then (A5) can be written as

$$0 \leq \pi(C_{-j}) - \Phi(C_{-j}) + \Omega . \tag{A7}$$

To show that (A1) holds, it suffices to show that $\Omega \leq 0$. It is easy to establish that $\Omega < 0$ for $b_j = 0$. Furthermore, $\frac{d\Omega}{db_j} \leq 0$ in the interval $[0, \frac{n-2}{n-1} \sum_{i \in C_{-j}} b_i)$. Hence, $\Omega < 0$ for $0 \leq b_j \leq \frac{n-2}{n-1} \sum_{i \in C_{-j}} b_i$

Now, note that we can choose j such that $b_j \leq b_i$ for all $i \in C_{-j}$. Hence, we have $b_j \leq \frac{1}{n-1} \sum_{i \in C_{-j}} b_i$. Furthermore, $\frac{1}{n-1} \sum_{i \in C_{-j}} b_i < \frac{n-2}{n-1} \sum_{i \in C_{-j}} b_i$ for $n \geq 4$. Hence, we can always find a player *j* in *C* such that $b_j \leq \frac{n-2}{n-1} \sum_{i \in C_{-j}} b_i$. For this value of b_j we have $\Omega < 0$. This establishes (A1). QED.

Proof of Proposition 3: We show that if a player's marginal benefit is sufficiently large, then the grand coalition ($C = N$) will be stable. By definition the grand coalition is externally stable. We only need to check for internal stability. Consider player *j*. From (12) we obtain

$$\begin{aligned}\pi(C) - \Phi(C) = & -\tfrac{1}{2}\left(\sum_{i \in C_{-j}} b_i\right)^2 \sum_{i \in C_{-j}} \frac{1}{a_i} - \tfrac{3}{2} \sum_{i \in C_{-j}} \frac{b_i^2}{a_i} + \sum_{i \in C_{-j}} b_i \sum_{i \in C_{-j}} \frac{b_i}{a_i} + \sum_{i \in C_{-j}} b_i^2 \sum_{i \in C_{-j}} \frac{1}{a_i} \\ & + \tfrac{1}{2} b_j^2 \sum_{i \in C_{-j}} \frac{1}{a_i} - b_j \sum_{i \in C_{-j}} b_i \sum_{i \in C_{-j}} \frac{1}{a_i} + b_j \sum_{i \in C_{-j}} \frac{b_i}{a_i} \\ & - \tfrac{1}{2}\left(\sum_{i \in C_{-j}} b_i\right)^2 \frac{1}{a_j} + \sum_{i \in C_{-j}} b_i^2 \frac{1}{a_j}.\end{aligned} \tag{A8}$$

Inspection of (A8) reveals that $\pi(C) - \Phi(C) \geq 0$ for sufficiently large b_j. QED.

Remark: In the simple case where $a_i = 1$ for all $i \in N$, internal stability of the grand coalition is satisfied if and only if

$$b_j \geq \frac{n-2}{n-1} \sum_{i \in C_{-j}} b_i + \sqrt{\left(\frac{(n-2)^2}{(n-1)^2} + \frac{n-2}{n-1}\right)\left(\sum_{i \in C_{-j}} b_i\right)^2 - \frac{2n-3}{n-1} \sum_{i \in C_{-j}} b_i^2}\,. \tag{A9}$$

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