Uniqueness of Coalitional Equilibria

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Summary

We provide an existence and a uniqueness result for coalitional equilibria of a game in strategic form. Both results are illustrated for a public good game and a homogeneous Cournot-oligopoly game.

Keywords: Existence and uniqueness of coalitional equilibrium, Game in strategic form

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Introduction

Recent developments in cooperative game theory analyse the formation of coalitions in the context of externalities based on the partition or valuation function (see for instance Bloch (2003) and Yi (1997)). Typical examples include Cournot-oligopolies, public good agreements, research coalitions, association of firms and customs unions. The partition (valuation) function assigns to each coalition structure, i.e., a partition of players, a vector of coalitional (individual) payoffs, called worth (valuations). For the partition but also for the valuation function it is assumed that coalitions chose their (economic) strategies by maximizing the sum of coalition members payoffs, taking the strategies of outsiders as given. Thus, coalitions play a Nash equilibrium that sometimes is referred to as coalitional equilibrium. Hence, a necessary condition for the analysis of stable coalitions is that a coalitional equilibrium exists for each coalition structure. Moreover, a convenient and often implicitly assumed condition is that the coalitional equilibrium for each coalition structure is unique which implies unique worth and valuations.

Though existence proofs can be found for example in Ray and Vohra (1997), they all are technical. Therefore, we provide with Theorem 1 an existence result that can be immediately applied to most economic models with a simple proof. To the best of our knowledge, uniqueness of coalitional equilibrium has not been addressed so far. With Theorem 2 we show how a not so well-known uniqueness result of Corchón (1996) can be generalized for this purpose. We apply our results to public good agreements and homogeneous Cournot-oligopolies. It turns out that in the latter example uniqueness requires apart from Theorem 2 some additional arguments.

2 Coalitional Equilibria

Let Γ be a game in strategic form between $N(\geq 1)$ players, with X^i the strategy space of player i and f^i his payoff function. Thus, X^i is a non-empty set and f^i is a real-valued function with domain $\mathbf{X} := X^1 \times \cdots \times X^N$. A coalition is a subset of $\mathcal{N} := \{1, \ldots, N\}$. A coalition structure $\mathcal{C}$ is a set consisting of disjoint non-empty coalitions whose union is $\mathcal{N}$. If S is a coalition, say, $S = \{s_1, \ldots, s_l\}$ with $s_1 < \cdots < s_l$, we define $\mathbf{X}^S := X^{s_1} \times \cdots \times X^{s_l}$. Note that $\mathbf{X}^{\mathcal{N}} = \mathbf{X}$. If S is a coalition, we write $\widehat{S} := \mathcal{N} \setminus S$. Sometimes, we identify $\mathbf{X}$ with $\mathbf{X}^S \times \mathbf{X}^{\widehat{S}}$ and then write $\mathbf{x} = (\mathbf{x}^S; \mathbf{x}^{\widehat{S}}) \in \mathbf{X}$.

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For $S \neq \emptyset$, define the function $F^S : \mathbf{X} \to \mathbb{R}$ by $F^S := \sum_{j \in S} f^j$. When $\mathbf{x} = (\mathbf{a}; \mathbf{b}) \in \mathbf{X}^S \times \mathbf{X}^{\widehat{S}}$ (and we like to see $\mathbf{b}$ as a parameter), we also write $F^S_{\mathbf{b}}(\mathbf{a})$ instead of $F^S(\mathbf{a}; \mathbf{b})$; so $F^S_{\mathbf{b}} : \mathbf{X}^S \to \mathbb{R}$. We define the correspondence $R^S : \mathbf{X}^{\widehat{S}} \multimap \mathbf{X}^S$ by $R^S(\mathbf{b}) := \operatorname{argmax} F^S_{\mathbf{b}}$.

Definition 1 Given a coalition structure $\mathcal{C}$, $\mathbf{n} \in \mathbf{X}$ is called a $\mathcal{C}$-equilibrium if $\mathbf{n}^S \in R^S(\mathbf{n}^{\widehat{S}})$ $(S \in \mathcal{C})$. $\diamond$

3 Existence and Uniqueness

Theorem 1 *Fix a coalition structure $\mathcal{C}$. If each strategy set X^i is compact and convex, each payoff function f^i is continuous and the functions $F^S_{\mathbf{b}}$ are quasi-concave, then there exists a $\mathcal{C}$-equilibrium.* $\diamond$

Proof.— Let $C^1, \ldots, C^k$ be the elements of $\mathcal{C}$. Define the mapping $\phi_{\mathcal{C}} : \mathbf{X}^{C^1} \times \cdots \times \mathbf{X}^{C^k} \to \mathbf{X}$ by $\phi_{\mathcal{C}}(\mathbf{x}^{C^1}, \ldots, \mathbf{x}^{C^k}) := \mathbf{x}$ and the correspondence $\mathbf{R}_{\mathcal{C}} : \mathbf{X} \multimap \mathbf{X}$ by $\mathbf{R}_{\mathcal{C}}(\mathbf{x}) := \phi_{\mathcal{C}}(R^{C^1}(\mathbf{x}^{\widehat{C^1}}) \times \cdots \times R^{C^k}(\mathbf{x}^{\widehat{C^k}}))$. Then, we have for $\mathbf{n} \in \mathbf{X}$: $\mathbf{n}$ is a $\mathcal{C}$-equilibrium $\Leftrightarrow$ $\mathbf{n}$ is a fixed point of the correspondence $\mathbf{R}_{\mathcal{C}}$. Thus, the proof is done if we show that $\mathbf{R}_{\mathcal{C}}$ has a fixed point. $\mathbf{X}$ is non-empty and as a product of compact spaces compact. The quasi-concavity of $F^S_{\mathbf{b}}$ implies that the set $R^S(\mathbf{b})$ is convex and its continuity implies that $R^S(\mathbf{b})$ is non-empty and closed. The continuity also implies (using Berges' maximum theorem) that the correspondences R^{C^i} are upper semi-continuous. This implies that also the correspondence $\mathbf{R}_{\mathcal{C}}$ is at most singleton-valued, convex-valued, closed-valued and upper semi-continuous, as desired for applying Kakutani's fixed point theorem. $\square$

The next theorem provides sufficient conditions for the uniqueness of a $\mathcal{C}$-equilibrium. An obvious modification of these conditions implies uniqueness of coalitional equilibria for each coalition structure.

Theorem 2 *Consider a game in strategic form Γ where each strategy set X^i is an interval of $\mathbb{R}$ containing more than one point. Fix a coalition structure $\mathcal{C}$. Suppose for each $S \in \mathcal{C}$ and $i \in S$ that the partial derivative of the function F^S with respect to i exists as an element of $\overline{\mathbb{R}} := \mathbb{R} \cup \{-\infty, +\infty\}$. Furthermore, suppose there exists an increasing function[1] $\varphi : \mathbf{X} \to \mathbb{R}$ and with $Y := \varphi(\mathbf{X})$, for each $S \in \mathcal{C}$ and $i \in S$ a function $\mathcal{T}^i_S : X^i \times Y \to \overline{\mathbb{R}}$ that is strictly decreasing in its first and decreasing in its second variable such that for each $\mathbf{x} \in \mathbf{X}$*

$$\frac{\partial F^S}{\partial x^i}(\mathbf{x}) = \mathcal{T}^i_S(x^i, \varphi(\mathbf{x}))$$

holds. Then,

1. *the function φ is constant on the set of all $\mathcal{C}$-equilibria and*
2. *if φ is strictly increasing, then there exists at most one $\mathcal{C}$-equilibrium.* $\diamond$

Proof.— Let $\mathbf{x}_*$ and $\mathbf{x}_\bullet$ be $\mathcal{C}$-equilibria. We may suppose that $y_* := \varphi(\mathbf{x}_*) \geq \varphi(\mathbf{x}_\bullet) =: y_\bullet$.

First, we prove that for all $S \in \mathcal{C}$ and $i \in S$ the inequality $x^i_* \leq x^i_\bullet$ holds. If $x^i_* = \inf X^i$ or $x^i_\bullet = \sup X^i$, then this result holds. Otherwise, x^i_* is not a left boundary point of X^i and $x^i_\bullet$ is not a right boundary point of X^i. Because $\mathbf{x}_*$ is a $\mathcal{C}$-equilibrium, $\mathbf{x}^S_*$ is a maximizer of the function $F^S_{\mathbf{x}^{\widehat{S}}_*}$. This implies that x^i_* is a maximizer of the function $x^i \mapsto F^S(x^i; \mathbf{x}^{\hat{i}}_*)$ and therefore it follows that $0 \leq \frac{\partial F^S}{\partial x^i}(\mathbf{x}_*) = \mathcal{T}^i_S(x^i_*, y_*)$. By the same token, $0 \geq \frac{\partial F^S}{\partial x^i}(\mathbf{x}_\bullet) = \mathcal{T}^i_S(x^i_\bullet, y_\bullet)$. Therefore, $\mathcal{T}^i_S(x^i_*, y_*) \geq \mathcal{T}^i_S(x^i_\bullet, y_\bullet)$. Because $y_\bullet \leq y_*$, we have $\mathcal{T}^i_S(x^i_*, y_\bullet) \geq \mathcal{T}^i_S(x^i_*, y_*)$. Thus, $\mathcal{T}^i_S(x^i_*, y_\bullet) \geq \mathcal{T}^i_S(x^i_\bullet, y_\bullet)$. Because $\mathcal{T}^i_S$ is strictly decreasing in x^i we have $x^i_* \leq x^i_\bullet$. Now we even may conclude that $\mathbf{x}_* \leq \mathbf{x}_\bullet$.

We now have $\varphi(\mathbf{x}_*) \leq \varphi(\mathbf{x}_\bullet)$. Thus, $\varphi(\mathbf{x}_*) = \varphi(\mathbf{x}_\bullet)$ and the proof of 1 is complete. If φ is strictly increasing, then $\mathbf{x}_* \leq \mathbf{x}_\bullet$ together with $\varphi(\mathbf{x}_*) = \varphi(\mathbf{x}_\bullet)$ implies that $\mathbf{x}_* = \mathbf{x}_\bullet$, which proves 2. $\square$

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[1] This means that for $\mathbf{a} = (a_1, \ldots, a_n),\ \mathbf{b} = (b_1, \ldots, b_n) \in \mathbf{X}$ we have $\mathbf{a} \geq \mathbf{b}$ (i.e., $a_i \geq b_i$ for all i) $\Rightarrow\ \varphi(\mathbf{a}) \geq \varphi(\mathbf{b})$. Furthermore, φ is strictly increasing means that for $\mathbf{a}, \mathbf{b} \in \mathbf{X}$ we have $\mathbf{a} > \mathbf{b}$ (i.e., $a_i \geq b_i$ for all i with at least one inequality strict) $\Rightarrow\ \varphi(\mathbf{a}) > \varphi(\mathbf{b})$.

4 Applications

In both applications which are general versions of games considered for instance in Bloch (2003) and Yi (1997), we analyse a game in strategic form with $X^i := \mathbb{R}_+$ or with $X^i := [0, m^i]$ (with $m^i > 0$).

Public Good Game:

$$f^i(x^1, \dots, x^N) := \beta^i(\sum_{l=1}^{N} x^l) - \gamma^i(x^i).$$

The functions $\beta^i : \sum_{l=1}^{N} X^l \to \mathbb{R}$ and $\gamma^i : X^i \to \mathbb{R}$ are continuous and strictly increasing. β^i will be called *benefit function* and γ^i *cost function*.

Theorem 3 *Consider a public good game with concave benefit functions and with strictly convex cost functions. Fix a coalition structure $\mathcal{C}$.*

1. *If each strategy space is compact, then the game has a $\mathcal{C}$-equilibrium.*
2. *If each benefit and cost function is differentiable, then the game has at most one $\mathcal{C}$-equilibrium.* $\diamond$

Proof.— 1. We apply Theorem 1. The only thing that may not be clear is the quasi-concavity of $F^S_{\mathbf{b}}$. Well, with $z := \sum_{l \in \widehat{S}} b^l$, we have

$$F^S_{\mathbf{b}}(\mathbf{a}) = \sum_{j\in S} \beta^j(z + \sum_{l \in S} a^l) + \sum_{j \in S} -\gamma^j(a^j).$$

The first sum is a sum of concave functions and therefore concave. The second sum is a strictly concave function. Thus, $F^S_{\mathbf{b}}$ is even strictly concave.

2. First observe that $\frac{\partial F^S}{\partial x^i}(\mathbf{a}; \mathbf{b}) = \sum_{j \in S} \beta^{j\prime}(\sum_{l\in S} a^l + \sum_{l \in \widehat{S}} b^l) - \gamma^{i\prime}(a^i)$. Next, we apply Theorem 2(2) with $\varphi(\mathbf{x}) := \sum_{l=1}^{N} x^l$ and $T^i_S(x^i, y) := \sum_{j \in S} \beta^{j\prime}(y) - \gamma^{i\prime}(x^i)$. $\square$

Homogeneous Cournot-oligopoly Game:

$$f^i(x^1, \dots, x^N) := p(x^1 + \cdots + x^N)x^i - c^i(x^i).$$

The function $p : \sum_{l=1}^{N} X^l \to \mathbb{R}_+$ is decreasing and continuous, and $c^i : X^i \to \mathbb{R}_+$ is continuous and strictly increasing. p is called *inverse demand function* and c^i *cost function*.

Theorem 4 *Consider a homogeneous Cournot-oligopoly game with convex cost functions and a concave inverse demand function. Fix a coalition structure $\mathcal{C}$.*

1. *If each strategy space is compact, then the game has a $\mathcal{C}$-equilibrium.*
2. *If p is differentiable with $p' < 0$, each cost function is differentiable and each $S \in \mathcal{C}$ contains a player with a strictly convex cost function, then the game has at most one interior $\mathcal{C}$-equilibrium.* $\diamond$

Proof.— 1. We apply Theorem 1. The only thing that may be not clear is the condition on $F^S_{\mathbf{b}}$. With $z := \sum_{l \in \widehat{S}} b^l$, we have

$$F^S_{\mathbf{b}}(\mathbf{a}) = \sum_{j \in S} p(\sum_{l \in S} a^l + z)a^j - \sum_{j\in S} c^j(a^j).$$

The second sum is a convex function of $\mathbf{a}$ while it is a sum of convex functions of each of the separate variables. Therefore, the proof is complete if we can show that the first sum is concave. For this in turn it is sufficient to prove that for each $j \in S$ the function $a^j \mapsto p(\sum_{l\in S} a^l + z)a^j$ is concave. Note that this function is a function on $X^i \subseteq \mathbb{R}_+$ and is a product of a decreasing concave function of a^j multiplied by a^j; such a product is known to be also concave.

2. Given $S \in \mathcal{C}$, define the function $g : \mathbf{X}^S \to \mathbb{R}$ by $g(\mathbf{x}^S) := \sum_{i\in S} c^i(x^i)$ and given $K \in \mathbb{R}$, denote $B_K := \{\mathbf{a}^S \in \mathbb{R}^{\#S} \mid \sum_{l \in S} a^l = K\}$. Let $\mathcal{K}$ be the set of $K \in \mathbb{R}$ for which $\mathbf{X}^S \cap B_K \neq \emptyset$. For each

$K \in \mathcal{K}$ the restricted function $g \restriction B_K$ has a unique minimizer $\mathbf{m}(K)$. (Indeed, we have a continuous strictly convex function on a non-empty compact convex subset of $\mathbb{R}^{\#S}$.) Denote by $\mathcal{K}'$ the set of elements $K \in \mathcal{K}$ for which $\mathbf{m}(K)$ is in the interior of $\mathbf{X}^S$. Now define $\mathcal{M}^S : \mathcal{K}' \to \mathbb{R}$ by

$$\mathcal{M}^S(K) := \frac{1}{\#S} \sum_{i \in S} c^{i\prime}(m^i(K)).$$

$\mathcal{M}^S$ is strictly increasing. In order to prove this, fix $K_1, K_2 \in \mathcal{K}'$ with $K_1 < K_2$. It is sufficient to prove that $c^{i\prime}(m^i(K_1)) < c^{i\prime}(m^i(K_2))$ $(i \in S)$. Because $\sum_{l \in S} m^l(K_1) = K_1 < K_2 = \sum_{l \in S} m^l(K_2)$, there exists $j \in S$ such that $m^j(K_1) < m^j(K_2)$. Noting that $\mathbf{m}(K)$ is interior, we find for $p = 1, 2$ (applying the method of Lagrange) $c^{i\prime}(m^i(K_p)) = c^{j\prime}(m^j(K_p))$ $(i \in S)$. Because $c^{j\prime}$ is strictly increasing, $c^{i\prime}(m^k(K_1)) < c^{i\prime}(m^k(K_2))$ for all i.

Using this preparation, we now prove the statement. Suppose $\mathbf{x}_*$ and $\mathbf{x}_\bullet$ are interior $\mathcal{C}$-equilibria. We may suppose that $y_* := \sum_{l=1}^N x_*^l \geq \sum_{l=1}^N x_\bullet^l =: y_\bullet$. Note that for $\star = *, \bullet$, we have: $\mathbf{x}_\star^S$ is the unique maximizer of the (strictly quasi-concave) function $F^S_{\mathbf{x}_\star^{\widehat{S}}} : \mathbf{X}^S \to \mathbb{R}$, i.e. of the function $\mathbf{a}^S \mapsto p(\sum_{l \in S} a^l + \sum_{l \in \widehat{S}} x_\star^l) \sum_{l \in S} a^l - \sum_{l \in S} c^l(a^l)$. With $w_\star^S := \sum_{l \in S} x_\star^l$, $\mathbf{x}_\star^S$ is a minimizer of the function $\mathbf{X}^S \cap B_{w_\star^S} \to \mathbb{R}$ defined by $\mathbf{a} \mapsto \sum_{l \in S} c^l(a^l)$. Hence, by the definition of $\mathcal{M}^S$, we have

$$\frac{1}{\#S} \sum_{i \in S} c^{i\prime}(\mathbf{x}_\star^S) = \mathcal{M}^S(w_\star^S).$$

Because $\mathbf{x}_\star^S$ is for each $S \in \mathcal{C}$ a maximizer of the function $F^S_{\mathbf{x}_\star^{\widehat{S}}}$, it follows that for each $i \in S$, $x_\star^i$ is a maximizer of the function $x^i \mapsto F^S(x^i; \mathbf{x}_\star^{\hat{\imath}})$. Because $x_\star^i$ is interior, it follows that

$$0 = \frac{\partial F^S}{\partial x^i}(\mathbf{x}_\star) = p'(y_\star) w_*^S + p(y_\star) - c^{i\prime}(x_\star^i). \qquad \smile$$

Therefore for each $S \in \mathcal{C}$, we have $p'(y_\star) w_\star^S + p(y_\star) = \frac{1}{\#S} \sum_{i \in S} c^{i\prime}(x_\star^i) = \mathcal{M}^S(w_\star^S)$. We now prove that $w_*^S \leq w_\bullet^S$ $(S \in \mathcal{C})$. Fix $S \in \mathcal{C}$. Because $y_\bullet \leq y_*$ and p and p' are decreasing, it follows that

$$p'(y_\bullet) w_*^S + p(y_\bullet) - \mathcal{M}^S(w_*^S) \geq p'(y_*) w_*^S + p(y_*) - \mathcal{M}^S(w_*^S) = p'(y_\bullet) w_\bullet^S + p(y_\bullet) - \mathcal{M}^S(w_\bullet^S).$$

Because the function $\mathbb{R}_+ \to \mathbb{R}$ defined by

$$w \mapsto p'(y_\bullet) w + p(y_\bullet) - \mathcal{M}^S(w)$$

is strictly decreasing, $w_*^S \leq w_\bullet^S$ must hold. Because we have this inequality for each $S \in \mathcal{C}$, it follows that $y_* \leq y_\bullet$. Therefore, $y_* = y_\bullet$, and hence $\sum_{S \in \mathcal{C}} w_*^S = \sum_{S \in \mathcal{C}} w_\bullet^S$. This in turn implies that even $w_*^S = w_\bullet^S$ must hold for each $S \in \mathcal{C}$. Now $x_*^i = x_\bullet^i$ for all i by ☺. □

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