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On the Stability of Cooperation Structures

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Summary

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JEL: C71, C72
Keywords: Cooperation structure, graph, Myerson value, stability, potential

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Abstract

This paper studies the payoff structure of stable cooperation structures in link formation games. Players choose non-cooperatively with whom they want to form a link, and the payoffs are given by the Myerson value of the cooperation structure obtained. We characterize the class of TU-games that ensure the stability of the full cooperation structure, which turns out to be much larger than the class of superadditive TU-games. We then provide an exact characterization of the Moderer and Shapley potential of the link formation game, and establish its equivalence with the potential as defined by Hart and Mas-Colell [*Econometrica* **57** (1989), 589–614]. We use this result to show that stable but Pareto dominated graphs can emerge under simple best-response dynamics.

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1 Introduction

In the last few years, the economic theory literature witnessed a growing interest on networks, with the purpose to understand how networks emerge, and to study their stability and efficiency properties.[1] Here, networks, also called cooperation structures, represent situations in which players may cooperate, or communicate only with a subset of the population. An interesting feature of these situations is that two players having a relationship may not have a relationship with the same subset of players. Cooperation structures are usually described with (non-directed) graphs, whose vertices represent players and edges (or links) represent the relationships players have between each other.

Among all the contributions on that topic, the work of Aumann and Myerson [1] has received particular attention. In their seminal paper, Aumann and Myerson proposed a model of endogenous cooperation structure, that was associating in a subtle way both cooperative and non-cooperative games. That is, the cooperation structure is modeled by means of a cooperative game, but it is formed in a non-cooperative way. The building block of Aumann and Myerson's model, which became common to most of the so-called **link formation games**,[2] is that a link between two players is formed only if they both want it. In such games a player's strategy is the set of players with whom she wants to form a link, and players' payoffs are given by the Myerson value [15] in the cooperation structure thus obtained. Since Aumann and Myerson's game is an extensive form game, a major drawback of their approach is that the order of play has to bet set exogenously. Later, Qin [16] reformulated Aumann and Myerson's game as a normal-form game. The main results obtained by Qin' are that *(i)* the game admits a potential — in the sense of Monderer and Shapley [14]; and *(ii)* if the underlying TU-game is superadditive, then the full cooperation structure (each player cooperates with all the other players) is stable in the sense that no player can profitably deviate by severing her links or any part thereof.

The purpose of this paper is to scrutinize the relationship between the stability of cooperation structures and the payoff structure of the game of link formation. Since this latter is built upon a cooperative TU-game, the properties we look for simply consists of designing the class of cooperative games that ensure that some specific cooperation structure is stable. Among all the possible cooperation structures there is one on which several papers (including this one) have brought specific attention: the full cooperation structure, which is the structure where all players are linked between each

[1]See Jackson and van den Nouweland [10] for a recent contribution about such issues and the references therein.

[2]See among others Jackson and Wolinsky [12], Dutta and Mutuswami [4], or Jackson and Watts [11] who used the same principle in their models.

other. The motivation for studying this structure is twofold. First, in many situations, the full cooperation structure is the efficient one, and as such, one would like it to be the stable one, too. But if for some reasons, like when there are congestion effects, the full cooperation structure is not efficient, then is seems natural to see if it is stable, and if so, whether or not simple dynamics do select this structure. The second reason is given by the choice of the stability concept. In this paper, like Qin [16], we do use as a stability concept the Nash equilibrium. A network is said to be stable if there is no player who can be better off by breaking some of his links and/or making new links. However, a new link between two players, say i and j is made only if both i and j want to make a link with j and i respectively. If player j's strategy is such that she does not want to make a link with i then, whatever the decision of i, there will not be any link between i and j. It follows that any network where any player does want to break a link is Nash-stable.[3] In other words, the Nash-stability, which is employed here, is more relevant in those cases where the only possibility left to the players is to break links, i.e., the full cooperation structure.

A first result we propose is a complete characterization of the class of TU-games that admit a stable full cooperation structure. It turns out that this class is much larger than the class of superadditive games. This is to be contrasted with other papers (e.g., [16] and [5]) that focused on superadditive environments only. More precisely, we show that the full cooperation structure is stable if and only if the (Shapley) value of each player is individually rational and the TU-game is superadditive for two-player coalitions only. In particular, this implies that if, for some TU-game (N, v) and two players i and j, we have $v(\{i, j\}) < v(\{i\}) + v(\{j\})$, then the full cooperation structure is not stable. This result suggests that "small coalitions" have a greater role in the stability of the full cooperation structure than bigger ones.[4] Nonetheless, this result also shows that the underlying TU-game does not need to be superadditive to ensure the stability of the full cooperation structure. This is, we believe, an interesting property given that non-superadditive economic environments abound. Such environments are for instance when there are congestion effects in the production of public goods. Another case that can generate non-superadditivity is when there are inefficiencies in decision making in large organization. In large firms or large organizations, increasing return to scale can be dominated by the cost of coordination (see Guesnerie and Oddou [6, 7, 8]).

A second set of results presented in this paper concerns the potential(s) of the link formation game. This approach follows that of Qin, who showed that this game admits a potential —in the sense of Monderer and Shap-

[3] For instance, if the TU-game is superadditive *all* networks are Nash-stable.

[4] In fact, all coalitions do matter since whether or not the Shapley value of each player is individually rational depends on the worth of *all* coalitions.

ley [14], henceforth MS-potential— if and only if the allocation rule used in the underlying TU-game is the Myerson value. In this paper, we propose a formula for the potential, and use it to derive further results about the stability of cooperation structures. The existence of an MS-potential is quite appealing,[5] since this latter has strong learning properties. That is, best-response and fictitious play learning processes converge to equilibria of the game, and these equilibria are those maximizing the MS-potential.[6] A second result concerning the MS-potential is its equivalence with the potential of Hart and Mas-Colell [9] —henceforth HM-potential — which, contrary to that of Monderer and Shapley, is a solution concept for cooperative games. At first sight, this result is quite surprising, since the two potentials are apparently two different mathematical objects. Nevertheless, the structure of the link formation game makes this result quite predictable. First, both concepts are built upon marginal variation of the payoffs. Second, Hart and Mas-Colell showed that their potential is closely related to the Shapley value, which is precisely the allocation rule used to compute players' payoffs in the link formation game, and thus the MS-potential. Moreover, it is worth to point out that a similar result has already been observed by Monderer and Shapley [14, theorems 6.1 and 6.2], and Ui [17].

The paper is organized as follows. In section 2 we present the framework. In section 3 we define the game of endogenous formation of cooperation structure. Our first characterization result is presented in section 4. Section 5 is devoted to the analysis of the potentials of the game. We study an example in section 6 and conclude in section 7.

2 Definitions

A transferable utility game (or a TU-game) is defined by a couple (N, v) where $N = \{1, \ldots, n\}$ is the set of players, and $v : 2^N \to \mathbb{R}$ is the characteristic function, with the convention that $v(\varnothing) \equiv 0$). The number $v(S)$ is the worth of coalition $S \in 2^N$. Given a game (N, v) and a subset of players S, (S, v) is the sub-game obtained by restricting v to subsets of S only. If N, R, S, T, $\ldots$ are coalitions, then n, r, s, t, $\ldots$ denote their respective size. The space of all TU-games with the set of players N is denoted by Γ_N.

We assume that players are able to establish meaningful relationships with a subset of players, and we call the set of all private relationships a **cooperation structure**. A useful way to represent cooperation structures is by a non-directed graph, whose vertices represent players and whose edges represent the relationships that players have between each other.

[5]Not all games admit an MS-potential.

[6]See Blume [2] and Monderer and Shapley [14, 13] for results on the learning properties of the potential, and Jackson and Watts [11] for a study of dynamic network formation with myopic players.

We define a graph, g, as a set of links between players. We write $i{:}j \in g$ when i and j are linked in g. Two players i and j are indirectly linked in g if there exists a sequence $i_1, \ldots, i_k$ in N, with $k \geq 3$, such that $i = i_1$, $i_{t-1}{:}i_t$ for all $t = 2, \ldots, k$, and $i_k = j$. The sequence $i_1, \ldots, i_k$ is called a path. Two players are said to be **connected** if they are (indirectly) linked. A coalition S is said to be connected if any pair of players $i, j \in S$ is connected by a path involving only players in S. We denote by GR_N the set of all graphs, by g_N the complete graph, i.e. the graph in which each player is linked with all other players,

$$g_N = \{i{:}j \mid i \in N \ , \ j \in N \ , \ i \neq j\}, \tag{1}$$

$$GR_N = \{g \mid g \subseteq g_N\} \ , \tag{2}$$

and $g_\varnothing$ the empty graph, i.e., there is no pair $i, j \in N$ such that $i{:}j \in g_\varnothing$.

For any graph g, $g \backslash \{i{:}j\}$ denotes the graph in which the link $i{:}j$ has been deleted, and $g \cup \{i{:}j\}$ is the graph to which the link $i{:}j$ has been added. We denote the graph g restricted to the set of vertices S by $g(S)$,

$$g(S) = \{i{:}j \mid i, j \in S, \ i{:}j \in g\}.$$

For any subset of players S, there is a unique partition of players that groups together players connected by $g(S)$. Such a partition is denoted by S/g. In other words, for any $i \in S$, the element of the partition S/g containing i also contains all other players that are connected to i by $g(S)$. A formal definition of this partition is defined as follows,

$$S/g = \{\{i \in S \mid i \text{ and } j \text{ are connected in } S \text{ by } g\} \mid j \in S\}.$$

3 The game

Qin's model works as follows. Given a TU-game (N, v), we allow players to choose who they want to cooperate, or communicate with. Hence, each player may have private relationships with a subset of the grand coalition only. More formally, we define a non-cooperative game

$$\mathscr{G}_h^{(N,v)} = < N, (\Sigma_i)_{i \in N}, (h_i)_{i \in N}) >,$$

where the TU-game (N, v) is called the **underlying game** of $\mathscr{G}_h^{(N,v)}$, and $\mathscr{G}_h^{(N,v)}$ is called a **link formation game**. As in (N, v), the set of players is N. The (finite) strategy set of player i is Σ_i, and $h = (h_i)_{i \in N}$ is the payoff function, $h : \times_{i \in N} \Sigma_i \to \mathbb{R}^N$.

3.1 Strategies

A strategy σ_i for player i is defined as a n-dimensional vector whose coordinates are either 0 or 1. When $\sigma_i(j) = 0$ player i does not wish to form a link with player j, while he would be glad to create such a link when $\sigma_i(j) = 1$. The ith coordinate of σ_i is assumed to be equal to zero, $\sigma_i(i) \equiv 0$. In other words, no player can make a link with herself. A link between players i and j is formed only if both i and j wish to create it: $\sigma_i(j) = \sigma_j(i) = 1$. We denote the n-tuple of strategies by $\sigma = (\sigma_1, \ldots, \sigma_n)$. Each $\sigma \in (\Sigma_i)_{i \in N}$ gives a unique cooperation structure $g(\sigma)$,

$$g(\sigma) = \{i{:}j \mid \sigma_i(j) = \sigma_j(i) = 1\}.$$

For each cooperation structure g, players are rewarded using the Myerson value of the game (N, v) on g, denoted by the n-dimensional vector $\mu(v, g)$.

We design by σ^S the strategy profile such that *(i)* for all $i, j \in S$, $\sigma_i(j) = 1$ and $\sigma_j(i) = 1$; and *(ii)* for all $i \in S$ and $j \notin S$, $\sigma_i(j) = 0$ or $\sigma_j(i) = 0$. That is, $g(\sigma^S)$ is a graph such that all players in S are connected to each other and players not in S have no links.

3.2 The payoffs

Payoffs in the link formation game defined by Qin are given by the Myerson value [15], which is an allocation rule for TU-games with graphs. In order to compute the Myerson value for some game (N, v) and some cooperation structure g, we first need to define a characteristic function embedded on graphs,

$$\forall\, S \subseteq N, \quad (v/g)(S) = \sum_{T \in S/g} v(T). \tag{3}$$

The Myerson value is the unique allocation μ rule that satisfies the **Component Efficiency** axiom, $\forall S \in N/g,\ g \in GR_N,\ \sum_{i \in S} \mu_i(v, g) = v(S)$, and the **Fairness** axiom, $\forall\ g \in GR_N,\ i{:}j \in g,\ \mu_i(v, g) - \mu_i(v, g \backslash i{:}j) = \mu_j(v, g) - \mu_j(v, g \backslash i{:}j)$.

Myerson proved that his value is closely related to the Shapley value. Indeed, we have

$$\forall\ (N, v) \in \Gamma_N,\ \forall\ g \in GR_N \qquad \mu(v, g) = \varphi(v/g)\ , \tag{4}$$

where φ is the Shapley value. It is straightforward to see that for the full cooperation structure, $v/g_N = v$, and hence $\mu(v, g_N) = \varphi(v)$. Moreover, if some player i is not connected to anyone in the cooperation structure g, then $\mu_i(v, g) = v(\{i\})$. Note that it may happen that for some game (N, v) and some g, we have $\mu_i(v, g) < v(\{i\})$.

Thus, the payoff of a player in the game $\mathscr{G}_\mu^{(N,v)}$ under the strategy profile σ is her Myerson value of the corresponding cooperation structure,

$$h_i(\sigma) \equiv \mu_i(v, g(\sigma)). \tag{5}$$

4 The stability of cooperation structures

Consider now a cooperation structure g such that players i and j are not linked, i.e., $i{:}j \notin g$. Then, player i desires to link up with player j if and only if

$$\mu_i(v, g \cup \{i{:}j\}) \geq \mu_i(v, g). \tag{6}$$

Given that the Myerson value satisfies the Fairness axiom, it is readily verified that if (6) holds true for player i, then it also holds true for player j.[7]

A cooperation structure g is **stable** in Qin's sense if there is a strategy profiles σ such that $g(\sigma) = g$ and σ is a Nash equilibria of the game $\mathscr{G}_\mu^{(N,v)}$. This result was also obtained in a similar framework by Dutta, van den Nouweland, and Tijs [5].[8] We now show that this result can be generalized to a larger class of games.

Proposition 1 *Let (N, v) be a TU-game and μ the Myerson value. Then the full cooperation structure is stable if and only if $\mu_i(v, g_N) \geq v(\{i\})$ for all $i \in N$, and*

$$\sum_{T \subseteq S, T \ni i} \rho_T(v(T) - v(T \backslash \{i\}) - v(\{i\})) \geq 0 \tag{7}$$

where $\rho_S = \frac{(n-1)!(n-s)!}{n!}$.

Proof See the Appendix. ■

Proposition 1 says that if the Shapley value of each player in the game (N, v) is individually rational then g_N is stable if and only if the game (N, v) is "superadditive" for two-player coalitions. Hence, the two conditions — individual rationality and (7) — fully characterize the class of TU-games that ensure the stability of the full cooperation structure.

Qin showed that if the underlying TU-game is superadditive, then for any partition $\mathscr{P}$ of N, there is a Nash equilibrium σ game such that $N/g(\sigma) = \mathscr{P}$ — see [16, remark 2]. We now show that Qin's result can be extended.[9]

Proposition 2 *Let (N, v) be a superadditive TU-game. For any $g \subseteq g_N$, there exist a strategy profile σ such that $g = (\sigma) = g$ and σ is a Nash equilibrium of $\mathscr{G}_\mu^{(N,v)}$.*

Proof See the Appendix. ■

[7] Reciprocity may not hold if player i wants to link up with several players at a time.

[8] [5] employed several equilibrium concepts, (undominated Nash equilibrium, coalition-proof Nash equilibrium and Strong Nash equilibrium) and did not use a specific solution concept to analyze to equilibria of the game.

[9] Proposition 2 is actually a corollary of Proposition 1 in [5].

5 The potential

In his paper, Qin used Monderer and Shapley's potential [14] to study the stability of cooperation structures. He showed that a link formation game with an underlying TU-game admits an MS-potential if and only if the allocation rule that gives players' payoffs is the Myerson value. In this section, we propose a formula for the MS-potential, and show its equivalence with the potential of Hart and Mas-Colell [9].

Definition 1 *A potential in the sense of Monderer and Shapley, or MS-potential, for $\mathscr{G}_\mu^{(N,v)}$ is a function $P : \Sigma \to \mathbb{R}$ such that for any $i \in N$, $\sigma \in \Sigma$, and $\hat{\sigma}_i \in \Sigma_i$,*

$$h_i(\hat{\sigma}_i, \sigma_{-i}) - h_i(\sigma) = P(\hat{\sigma}_i, \sigma_{-i}) - P(\sigma) \tag{8}$$

A non-cooperative game $\gamma = (N, \Sigma, h)$, with player set N, Strategy space Σ and payoff functions $h = (h_i)_{i \in N}$ is a **potential game** if it admits an MS-potential.

Since the MS-potential is defined up to a constant, we can assign a value for the empty graph, and then recursively deduce its value for all graphs.

Proposition 3 *Let σ be any strategy profile, and let $g = g(\sigma)$.*

$$P(\sigma) = \sum_{S \subseteq N} \frac{(n-s)!(s-1)!}{n!} (v/g)(S) \ . \tag{9}$$

Clearly, the formula of the MS-potential is closely related to the Shapley value of the game. Nonetheless, it is easy to see that the potential in eq. (9) is also the potential as defined by Hart and Mas-Colell [9]. Their potential, defined upon cooperative games is defined as follows.

Definition 2 *A function $P^{HM} : \Gamma_N \to \mathbb{R}$ is a potential in the sense of Hart and Mas-Colell, or HM-potential, if it satisfies the following condition*

$$\sum_{i \in N} D_i P(N, v) = v(N) \ , \tag{10}$$

where $D_i P(N, v) = P(N, v) - P(N \backslash \{i\}, v)$.

Hart and Mas-Colell [9, eq. (2.5), p. 592] proved that the potential P^{HM} can be characterized (up to a constant) by the following equality:

$$P^{HM}(N, v) = \sum_{S \subseteq N} \frac{(n-s)!(s-1)!}{n!} v(S) \ . \tag{11}$$

We can then show the following result.

Proposition 4 *Let σ be any strategy profile, and $g = g(\sigma)$.*

$$P^{HM}(N, v/g) = P_v(g) \ .$$

Proof Observe that the potential P^{HM} is defined on games with full cooperation structures. Hence, to prove the proposition, it suffices to obtain the potential P^{HM} for any graph g. For any graph g, $(N, v/g) = (N, (v/g)/g_N)$. Thus,

$$P^{HM}(N, v/g) = \sum_{S \subseteq N} \frac{(n-s)!(s-1)!}{n!} (v/g)(S) \ . \tag{12}$$

Clearly, (9) and (12) do coincide, which proves the result. ■

A similar result has been already observed by Monderer and Shapley [14, theorems 6.1 and 6.2], and Ui [17]. Their proofs work in opposite directions. Monderer and Shapley proved that for any cooperative game we can construct a non-cooperative game (called *participation game*) such that it admits an MS-potential if and only if the allocation rule used in the original cooperative game (which serves to compute players' payoffs in the participation game) is the Shapley value. Conversely, Ui started from a non-cooperative game, and showed that we can construct an associated cooperative game with payoffs being given by the Shapley value if and only if the original game admits an MS-potential. Here, we took a different route, simply showing that the formula for the HM-potential and the MS-potential do coincide.

6 An example

As the following example shows, superadditivity of the game (N, v) is not necessary for the stability of the full cooperation structure.

Consider the following TU game (N, v) with $N = \{a, b, c, d\}$, and v defined by

$$v(S) = \begin{cases} 0 & \text{if } |S| = 1, \\ 180 & \text{if } |S| = 2, \\ 168 & \text{if } |S| = 3, \\ 144 & \text{if } |S| = 4. \end{cases}$$

The Myerson value of each player for the full cooperation structure is $\mu_i(v, g_N) = 36$, for $i = a, b, c, d$, which is obviously individually rational. Moreover, condition (7) is satisfied. Hence, Proposition 1 implies that the full cooperation structure is stable. Yet, it is obvious that the full cooperation structure is Pareto dominated, i.e. there is another cooperation structure (for instance $g' = \{a{:}b,\ c{:}d\}$) that yields a value of 90 to each player, which is strictly higher than the value when the full cooperation structure is formed.[10]

It turns out that this example has more to say. Consider the potential of the game. Since the game is symmetric, all graphs (and thus all the values of the potential) can be characterized by the number of links, and for the case when there are two, three or four links on the number of link per player. In table 1 when a graph has for distribution of links per player the value $3, 2, 2, 1$ it means that there is one player with three links, two players with two links and one player with one link. This yields the following values for the potential.

♯ of links	link distribution	P	♯ of links	link distribution	P
0	0,0,0,0	0	3	2,2,2,0	146
1	1,1,0,0	90	3	3,1,1,1	123
2	1,1,1,1	180	4	2,2,2,2	152
2	2,1,1,0	116	4	3,2,2,1	153
3	2,2,1,1	139	5	3,3,2,2	167
			6	3,3,3,3	182

Table 1: Values of the potential

This example is quite interesting since it shows that the complete graph does maximize the potential, although the game is not superadditive (it is even not monotonic). Yet we can see that the potential is maximum when the cooperation structure is complete.[11]

Further scrutiny shows that the complete graph can be obtained by fictitious play. For, consider the sequence of graphs $\bar{g} = \{g_1, g_2, \ldots, g_7\}$, where $g_1 = g_\varnothing$ and $g_7 = g_N$, with the following distribution of links:

It is easy to see that for any $h = 1, \ldots 6$, the graph g_{h+1} is obtained just by adding an additional link to g_h. Indeed, it is easy to construct an initial strategy profile such that each step is obtained from the previous one by just *one* deviation.[12] Clearly, for all $h = 1, \ldots 6$ $P(g_h) < P(g_{h+1})$. Hence, according to Monderer and Shapley's terminology, the sequence $\bar{g}$ in an *finite improvement path*, which reflects a myopic learning process.

[10] A similar result was obtained by Jackson and Wolinsky [12], who showed that some games $\mathscr{G}_\mu^{(N,v)}$ may have a stable cooperation structures that are not efficient, i.e. structures that do not maximize the worth of coalition(s).

[11] See Jackson and Wolinsky [12] for a related result showing that stable graphs are not necessarily those maximizing the total value.

[12] Recall that to make a link between i and j we must have $\sigma_i(j) = \sigma_j(i) = 1$. To see that the sequence can be obtained by a sequence of 6 best-response deviations, consider for instance that players a and b make the first link (the unique link in g_2). Then, we can start with the strategy profile σ such that $\sigma_a(b) = 0$ and $\sigma_b(a) = 1$. The deviating player is a, and doing so her payoff in g_2 is strictly higher than her payoff in g_1.

Graph	♯ of links	link distribution	Potential
g_1	0	0,0,0,0	0
g_2	1	1,1,0,0	90
g_3	2	2,1,1,0	116
g_4	3	2,2,1,1	139
g_5	4	2,2,2,2	152
g_6	5	3,3,2,2	167
g_7	6	3,3,3,3	182

Table 2: Distribution of links

7 Conclusion

We first showed that superadditivity (like monotonicity) are not necessary to obtained the stability of the full cooperation structure. In fact, the class of TU-games that admit full cooperation structure turns out to be very large. One relevent point is that small coalitions seem to have a particular role. It is often argued that the Nash equilibrium concept is not appropriate for this game since it admits too many stable cooperation structures. It it worth to point out that our result still holds if one uses Jackon and Wolinsky's [12] *pairwise stability* concept.[13] Our result is even more striking when we look at the potential of the game. As our example shows, neither monotonicity nor superadditivity are necessary to obtain the full cooperation as the stable cooperation structure when considering fictitious play. This amounts to say that simple best-response dynamics can yield players to build inefficient cooperation structure.

An other result we obtained is the equivalence of the potential of Monderer and Shapley[14], and that of Hart and Mas-Colell [9]. Since these two concepts are designed for two different frameworks (non-cooperative games for the former and cooperative games for the latter), it has been usually thought that the only common aspect they share was their name. The model analyzed in this paper allows us to study the two potentials proposed in the literature. To see this, it is important to have in mind how the link formation game is built. Recall that we start first with a *cooperative* TU-game. Hence, this game has an HM-potential. The second step consists of building a *non-cooperative* game of link formation, which allows us to study the MS-potential. It is worth pointing out that not all non-cooperative games admit a potential. However, Qin proved that this game *does* admit an MS-potential (if and only if the allocation rule is the Myerson value). In this paper, we showed that these two potential are identical (for this game). Though being quite surprising at first sight, this result can be

[13]When we look only at the full cooperation structure the pairwise stability concept and the Nash stability used in this paper do coincide.

expected. Indeed, both concepts are defined upon marginal differences in terms of payoffs. Hart and Mas-Colell showed that their potential is closely related to the Shapley value of the TU-game, and the Myerson value, which defines the payoffs in the link formation game, is known as being the Shapley value of some specific TU-game.

Appendix

In order to prove proposition 1, we introduce more definitions. For any cooperation structure g and players i and j such that $i{:}j \in g$, define the set

$$\mathbf{S}(g, i{:}j) = \{S \subseteq N \mid S/g = S \text{ and } S/(g \backslash \{i{:}j\}) \neq S\}.$$

In other words, $\mathbf{S}(g, i{:}j)$ is the set of coalitions S such that S is connected in $g(S)$ but is non-connected in $g(S) \backslash \{i{:}j\}$. When no confusion is possible, we write $\mathbf{S}(i{:}j)$ instead of $\mathbf{S}(g, i{:}j)$. In other words, $\mathbf{S}(i{:}j)$ represents the set of coalitions S that are connected thanks to $i{:}j$ when the graph is restricted to S.[14] Thus, for any $S \in \mathbf{S}(i{:}j)$, if $i{:}j$ is deleted, $S/(g \backslash \{i{:}j\} = \{S_i, S_j\})$, with S_i and S_j being the sets in $S/(g \backslash \{i{:}j\})$ that contain i and j respectively.

Proof of Proposition 1

Observe that there is a unique strategy profile σ^* such that $g(\sigma^*) = g_N$. Hence, σ^* is a Nash equilibrium if and only if no player breaks one or more links. Hence, it suffices to compare, for any player i, her payoffs under the strategy profile σ and under the strategy profile $(\sigma'_i, \sigma^*_{-i})$, where $\sigma'_i(j) = 0$ for at least one $j \in N \backslash \{i\}$.

Clearly, if the value of some player is not individually rational, then that player has an incentive to break up all her links (or any part thereof), and then the full cooperation structure is not stable. In other words, individual rationality is a necessary condition for the full cooperation structure to be stable. We now show that if the value of each player is individual rational, then stability is equivalent to condition (7).

We claim that for any graph g, if a player contemplates breaking a link, yielding g', the change of her payoff (i.e., her Myerson value) will only depend on the worth of the coalitions that are connected in g and not connected in g'. To see this, consider the value of player i for a cooperation structure g and $g \backslash \{i{:}j\}$:

$$\mu_i(v, g) = \sum_{S \ni i} \rho_S \left((v/g)(S) - (v/g)(S \backslash i)\right)$$

$$\mu_i(v, g \backslash \{i{:}j\}) = \sum_{S \ni i} \rho_S \left((v/g(\backslash \{i{:}j\}))(S) - (v/g(\backslash \{i{:}j\}))(S \backslash i)\right),$$

Notice that

[14] In graph terminology, we say that $\mathbf{S}(g, i{:}j)$ is the set of all subgraphs $\hat{g}$ of g such that the link $i{:}j$ is **critical** in $\hat{g}$ — see [3].

(i) $g/(S\backslash\{i\}) = (g\backslash\{i{:}j\})/(S\backslash\{i\})$,

(ii) $(g\backslash\{i{:}j\})/S \neq g/S$ when $i{:}j$ connects S in g, i.e., when $S \in \mathbf{S}(i{:}j)$,

(iii) $(g\backslash\{i{:}j\})/S = g/S$ when $i{:}j$ does not connects S in g.

Using equation (3) we deduce

(a) *(i)* $\Rightarrow \forall\, S \ni i,\ (v/g)(S\backslash\{i\}) = (v/(g\backslash\{i{:}j\}))(S\backslash\{i\})$,

(b) *(ii)* $\Rightarrow$ when $S \in \mathbf{S}(i{:}j)$, $(v/g\backslash\{i{:}j\})(S)$ and $(v/g)(S)$ may differ

(c) Let S such that $S/g = S$. Then *(iii)* $\Rightarrow (v/g\backslash\{i{:}j\})(S) = (v/g)(S)$ when $S \notin \mathbf{S}(i{:}j)$.

If $S/g \neq S$, then there is one element of S/g that contains i. Let $\hat{S}$ be this element. Clearly, for all $T \in S/g$ such that $T \neq \hat{S}$, we have $(v/g\backslash\{i{:}j\})(T) = (v/g)(T)$. Hence, when doing $(v/g)(S) - (v/g(\backslash\{i{:}j\}))(S)$ we can restrict to $\hat{S}$, and either we are in case *(b)* or in the first part of case *(c)*.

Combining these observations we obtain

$$\begin{aligned} & \mu_i(g) - \mu_i(g\backslash\{i{:}j\}) \geq 0 \\ \Leftrightarrow & \sum_{S \in \mathbf{S}(i:j)} \rho_S(v(S) - v(S_i) - v(S_j)) \geq 0, \end{aligned} \tag{13}$$

which proves the claim.

Observe that if $g = g_N$, then $\mathbf{S}(i{:}j) = \{\{i,j\}\}$. In other words, in the full cooperation structure, if a player i breaks a link with player j, the only coalition that becomes non-connected is $\{i,j\}$.

More generally, suppose that some player i severs her links in g_N with players $j \in T$, where T is some subset of $N\backslash\{i\}$. Then we have $\{\mathbf{S}(i{:}j)\}_{j\in T} = \{R \cup \{i\} : R \subseteq T\backslash\{i\}\}$.[15] This implies that i severs her links with players $j \in S \subseteq N\backslash\{i\}$ if, and only if

$$\sum_{T \subseteq S, T \ni i} \rho_T(v(T) - v(T\backslash\{i\}) - v(\{i\})) < 0 \tag{14}$$

As (14) holds for any $S \subseteq N\backslash\{i\}$, for any $i \in N$, the result follows. ■

Proof of Proposition 2 Consider any superadditive game (N, v) and any cooperation structure g. Hence, (13) always holds and we can deduce that no player wishes to break a link. Consider the following strategy profile. For each player $i \in N$, let $\sigma_i(j) = 0$ if $i{:}j \notin g$ and $\sigma_i^*(j) = 1$ if $i{:}j \in g$.

[15] That is, if i breaks her links with all players in T, yielding the network g, then for all R in $\{\mathbf{S}(i{:}j)\}_{j\in T}$ we have $(v/g)(R) = v(R\backslash\{i\}) + v(\{i\})$.

Because players do not sever links, if a player i deviates with the strategy $\hat{\sigma}$, it should be the case that for some j we have $\hat{\sigma}_i(j) = 1$ and $\sigma_i^*(j) = 0$. But deviations are individuals, which implies that $\sigma_j^*(i) = 0$. Hence, $g(\hat{\sigma}_i, \sigma_{-i}^*) = g$, and player's i payoff remains unchanged. Thus, i has no incentives to deviates. ■

Lemma 1 *Let g be a graph such that there exists a set of players* $\mathbf{S}$ *and a player $i \notin \hat{S}$ such that for all $j \in \hat{S}$, i and j are not connected. Then*

$$\mu_i(v, g, N) = \mu_i(v, g, N \backslash \mathbf{S}) \ . \tag{15}$$

Proof First, observe that if i is not connected to any player in $\hat{S}$, then it is also the case for any player that is connected to i.

We prove the lemma when $\hat{S}$ contains only one player, say j. When $\hat{S}$ contains more than one player, it suffices to repeat the argument presented below.

If we withdraw player j from the set of players, we have a new set of player N' of size $n' = n - 1$. With this new player set, we have (the right-hand side of equation (15))

$$\mu_i(v, g, N') = \sum_{R \ni i} \frac{(n' - r)!(r-1)!}{n'!} \left[(v/g)(R) - (v/g)(R \backslash \{i\})\right] \ . \tag{16}$$

We now compute the left-hand side of equation (15). Observe that for any $T \ni j$, $(v/g)(T) = (v/g)(T \backslash \{j\}) + (v)(\{j\})$.[16] Thus, we have for any $i \in N \backslash \hat{S}$

$$\begin{aligned} \mu_i(v, g, N) = & \sum_{\substack{R \ni i \\ j \notin R}} \rho(r) \left[(v/g)(R) - (v/g)(R \backslash \{i\})\right] \\ & \qquad - \sum_{\substack{R \ni i \\ j \in R}} \rho(r) \left[(v/g)(R \backslash \{j\}) - (v/g)(R \backslash \{i, j\})\right] \\ = & \sum_{\substack{R \ni i \\ j \notin R}} (\rho(r) + \rho(r+1)) \left[(v/g)(R) - (v/g)(R \backslash \{i\})\right] \ . \end{aligned} \tag{17}$$

Straightforward computation shows that

$$\rho(r) + \rho(r+1) = \frac{(n - 1 - r)!(r-1)!}{(n-1)!} = \frac{(n' - r)!(r-1)!}{n'!} \ . \tag{18}$$

Combining combining (17) and (18) we obtain (16). ■

[16]If $\hat{S}$ contains more than one player, then this equality becomes: for any $T \supset \hat{S}$, $(v/g)(T) = (v/g)(T \backslash \hat{S}) + (v)(\hat{S})$.

Lemma 2 *Assume that $P(\varnothing) \equiv 0$. Let S be a nonempty subset of N and let $g = g(\sigma^S)$. Then*

$$P(\sigma^S) = \sum_{i \in S} -\frac{s-1}{s} v(\{i\}) + \sum_{T \subseteq S \,:\, t \geq 2} \frac{(s-t)!(t-1)!}{s!} v(T) \; . \tag{19}$$

Proof We prove the lemma by induction on the size of S. Assume first that $S = \{i, j\}$. Consider the empty graph and the graph $g = g(\sigma^S)$. Since players i and j are the only players whose payoff changes between g and the empty graph, we have $P(\sigma^S) - P(\sigma^\varnothing) = \mu_i(v, g) - \mu_i(v, \varnothing)$. By lemma 1, we know that $\mu_h(v, g, N) = \mu_h(v, g, \{i, j\})$ for $h = i, j$. Thus, with the convention that $P(\varnothing) \equiv 0$, we obtain

$$\begin{aligned} P(\sigma^S) &= \mu_i(v, g) - \mu_i(v, \varnothing) \\ &= \varphi_i(v/g) - \varphi_i(v/\varnothing) \\ &= \frac{1}{2} v(\{i\}) + \frac{1}{2} \left[v(\{i, j\}) - v(\{j\}) \right] - v(\{i\}) \\ &= -\frac{1}{2} [v(\{i\}) + v(\{j\})] + \frac{1}{2} v(\{i, j\}) \end{aligned}$$

which completes the proof for the case $s = 2$.

Let S be any set of players of size three or more, and let $g = g(\sigma^S)$. By the induction hypothesis, the potential for the graph g is given by (19). Let $i \notin S$, and let $g' = g(\sigma^{S \cup \{i\}})$. We write S' for $S \cup \{i\}$. We have

$$\begin{aligned} & P(\sigma^{S'}) - P(\sigma^S) = \mu_i(v, g') - \mu_i(v, g) = \varphi_i(v/g') - \varphi_i(v/g). \\ \Leftrightarrow & P(\sigma^{S'}) = P(\sigma^S) + \varphi_i(v/g') - \varphi_i(v/g). \end{aligned} \tag{20}$$

Recall that

$$\begin{aligned} \varphi_i(v, g') &= \sum_{T \ni i} \frac{(n-t)!(t-1)!}{n!} [(v/g)(T) - (v/g)(T \backslash \{i\})] \; , \\ &= \sum_{T \subseteq S' \,:\, T \ni i} \frac{(s'-t)!(t-1)!}{s'!} [v(T) - v(T \backslash \{i\})] \; , \qquad \text{(A)} \\ \varphi_i(v, g) &= v(\{i\}) \; , \qquad \text{(B)} \\ P(\sigma^S) &= \sum_{j \in S} -\frac{s-1}{s} v(\{i\}) + \sum_{T \subseteq S \,:\, t \geq 2} \frac{(s-t)!(t-1)!}{s!} v(T) \; . \qquad \text{(C)} \end{aligned}$$

where (A) is obtained using lemma 1. Thus,

$$P(\sigma^{S'}) = (A) - (B) + (C) \; . \tag{21}$$

First, observe that $v(\{i\})$ is only present in (A) (for $T = \{i\}$) and (B). Thus, in $P(\sigma^{S'})$, the coefficient of $v(\{i\})$ is given by

$$\frac{(s'-t)!(t-1)!}{s'!} - 1 = \frac{(s'-1)!}{s'!} - 1 = -\frac{s'-1}{s},$$

where the first equality comes from the fact that $t = 1$.

We now compute the coefficient for $v(\{j\})$, $\forall j \in S$. For each $v(\{j\})$, it is given by

$$-\frac{(s'-t)!(t-1)!}{s'!} - \frac{s-1}{s} = -\frac{(s'-2)!}{s'!} - \frac{s'-2}{s'-1} = -\frac{s'-1}{s'} .$$

In order to compute the coefficient for coalitions $R \subseteq S$, we must take into account that when a coalition R appears in (A), $t = r + 1$, whereas in (C) we have $t = r$. Hence, the coefficient is given by

$$\begin{aligned} & -\frac{(s'-t-1)!t!}{s'!} + \frac{(s-t)!(t-1)!}{s!} \\ = & -\frac{(s'-t-1)!t!}{s'!} + \frac{(s'-t-1)!(t-1)!}{(s'-1)!} \\ = & -\frac{(s'-t)!(t-1)!}{s'!} . \end{aligned}$$

It remains to compute the coefficient for the coalitions T that include i **and** some players in S. It is easy to see that such coalitions only appear in (A). Thus we have,

$$P(\sigma^{S'}) = \sum_{j \in S'} -\frac{s'-1}{s'} v(\{j\}) + \sum_{T \subseteq S' \,:\, t \geq 2} \frac{(s'-t)!(t-1)!}{s'!} v(T) , \tag{22}$$

which completes the proof. ■

Lemma 3 *Assume that* $P(\varnothing) \equiv 0$. *Let* S *be a nonempty subset of* N *and let* $g = g(\sigma^S)$. *Then*

$$P(\sigma^S) = \sum_{i \in N} -\frac{n-1}{n} v(\{i\}) + \sum_{T \subseteq N \,:\, t \geq 2} \frac{(n-t)!(t-1)!}{n!} (v/g)(T) . \tag{23}$$

The difference between this lemma and lemma 2 is in the second summation. In lemma 2 the summation is done over $T \subseteq N$ and in lemma 3 the summation is done over $T \subseteq N$.

Proof We prove the lemma by induction on the size of S. Assume first that $S = \{i, j\}$. From the proof of lemma 2, we know that $P(\sigma^S) = -\frac{1}{2}[v(\{i\}) + v(\{j\})] + \frac{1}{2}v(\{i, j\})$. Using lemma 1 it is straightforward to see that in this case the following equality holds true

$$\begin{aligned} & \sum_{h \in S} -\frac{s-1}{s} v(\{h\}) + \sum_{T \subseteq S \,:\, t \geq 2} \frac{(s-t)!(t-1)!}{s!} v(T) \\ = & \sum_{i \in N} -\frac{n-1}{n} v(\{i\}) + \sum_{S \subseteq N \,:\, s \geq 2} \frac{(n-s)!(s-1)!}{n!} (v/g)(S) . \end{aligned}$$

Let S be any set of players of size three or more and lower than n (if $S = N$ then lemmata 2 and 3 are identical). Denote $P^S(\sigma)$ and $P^N(\sigma)$ the potential when the summation is done over S and N respectively (equations (19) and (23)).

By the induction hypothesis, $P^N(\sigma^S) = P^S(\sigma^S)$. Consider some $i \notin S$, and let $S' = S \cup \{i\}$, $g' = g(\sigma^{S'})$. We claim that $P^N(\sigma^{S'}) = P^{S'}(\sigma^{S'})$. We have

$$\begin{aligned} P^N(\sigma^{S'}) &\equiv P^N(\sigma^S) + \varphi_i(v/g', N) - \varphi_i(v/g, N) \\ &= P^S(\sigma^S) + \varphi_i(v/g', S') - \varphi_i(v/g,') \\ &= P^{S'}(\sigma^{S'}) \ , \end{aligned}$$

The first equality is simply the definition of the potential. The second and third equalities are respectively obtained using lemma 1,[17] and equation (20). ■

Let σ be any strategy profile, and let $g = g(\sigma)$. Denote by $P_v(\sigma)$ and $P_{v/g}(\sigma^N)$ the potential for the games $\mathscr{G}_\mu^{(N,v)}$ and $\mathscr{G}_\mu^{(N,v/g)}$ respectively.

Lemma 4 $P_v(\sigma) = P_{v/g}(\sigma^N)$

Proof Since the potential is deduced (up to a constant) from the payoffs of the game, it suffices to show that $\mu(v, g) = \mu(v/g, g_N)$, for all $g \subseteq g_N$. Recall that $\mu(v, g) = \varphi(v/g)$, and that $\mu(v, g_N) = \varphi(v)$. Hence, $\mu(v/g, g_N) = \varphi(v/g)$, which yields the desired equality. ■

Proof of proposition 3 From lemmata 4 and 3, it is easy to deduce that

$$P(\sigma) = \sum_{i \in N} -\frac{n-1}{n} v(\{i\}) + \sum_{S \subseteq N \,:\, s \geq 2} \frac{(n-s)!(s-1)!}{n!} (v/g)(S) \ .$$

Since the potential is defined up to a constant, it suffices to add $\sum_{i \in N} \frac{n-1}{n} v(\{i\})$ to the potential of any graph and the result follows. ■

[17] No player in S' is linked to a player in $N \backslash S'$.

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