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Frédéric Deroian

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Frédéric Deroian, *F.O.R.U.M Université Paris X*

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# Cost-Reducing Alliances and Local Spillovers


## Summary

Firms raise cost-reducing alliances before competing with each other, but cannot fully internalize the shared knowledge. When spillovers are local and transit through the network of alliances, stable architectures with a moderate level of asymmetry are identified.



**Keywords**: Oligopoly, Cost-Reducing alliances, Local spillovers, Network stability

**JEL Classification**: C70, L13, L20



*Address for correspondence*:

Frédéric Deroian
F.O.R.U.M  Université Paris X
Bâtiment K
200, avenue de la République
92001 Nanterre
France
Phone: +33140977805
Fax: +33140975907
E-mail: fderoian@u-paris10.fr

## 1 Introduction

We extend the model of Goyal and Joshi (2003) to involuntary spillovers. We assume that the knowledge generated by a technological alliance generates spillovers affecting a subset of firms distinct from the allied, and we examine three modes of spillover dissemination. In the benchmark case, spillovers affect the whole population of firms. By contrast, in the two latter spillovers spread through the network of alliances; they affect either the direct neighborhoods of the partners, or the whole component each partner is embedded in.

By introducing local spillovers, the proposed game contains both positive and negative externalities. This enables us to examine non monotonic impacts of network characteristics on profitability of link formation. As a preliminary remark, we observe that when spillovers disseminate globally, they have no particular influence on individual incentives to form alliances and the complete network emerges. Then, we test the spillovers' spreading through the network of alliances. This entails the formation of networks with moderate asymmetry and under-connected with regard to social welfare. When spillovers spread toward the direct neighborhood of the allied, we notably isolate a class of graphs containing a unique *incomplete* component. When spillovers spread in the whole component of the allied, the possible stable architectures are reduced to the union of complete components of distinct size; furthermore the size of stable components satisfies a non-monotonic relationship with respect to spillovers intensity.

This paper can be inserted in the literature on strategic cooperation. Beyond the fact our model extends Goyal and Joshi (2003)'s seminal work, the moderate level of asymmetry in the stable networks shall be compared with Calvo-Armengol (2004); This work provides a qualitatively similar conclusion in a model of job search, in which individual payoffs exhibit increasing return in own links and decreasing return in the partners' links. Second, the emergence of asymmetric and complete components (in the case spillovers affect the whole component of the partners) shall be compared with Bloch (1995). With respect to this work, a rather similar mechanism applies: the incitation to refuse a connection increases with the difference between the partner's and own component size. But, there is also a major difference: in our context small components (typically whose cardinal is less than half the population) may not coalesce. Further, the non-monotonicity of the set of stable networks with respect to spillovers' intensity is intrinsic to our context.

Section 2 presents the model, section 3 the results. The last section is an appendix providing all proofs.

## 2 The model

We consider an industry containing a set $N = \{1, ..., n\}$ of firms. We set up a standard two-periods game in which the first is devoted to the formation of cost-reducing alliances and the second to competition. For this purpose, we propose a spillover-augmented version of the game initiated by Goyal and Joshi (2003).

**Graphs.** We denote $[\cdot]$ as the floor operator and $|\cdot|$ means the cardinal of a set. A non directed graph represents the firms (the nodes) plus the set of bilateral alliances between the firms (the edges between nodes). We denote by $G$ the set of all non directed graphs with $n$ nodes. We shall abuse the notation by writing that some link $ij \in g$. We denote by $N_i(g)$ the set of agents with whom agent $i$ forms a link in the graph $g$ (agent $i$ is not included in the set by convention) and $\mu_i(g)$ represents the cardinal of this set. We need to define $v_{ij}(g) = |N_i(g) \cap N_j(g)|$, $v_{ij}(g) \in \{0, \cdots, n-2\}$, representing the number of common partners of agents $i$ and $j$ in the graph $g$.

Symbol $g - ij$ (resp. $g + ij$) shall denote the graph $g$ less (resp. plus) the link $ij$. The *subgraph* $A(g)$ of a graph $g$ is the graph containing agents in $A(g)$ plus all links involving in the graph $g$ the pairs of agent in $A(g)$. A *complete subgraph* is a subgraph such that every pair of agents in the subgraph forms a link. A *path* in the graph $g$ is a sequence of nodes $\{a_0, \cdots, a_p\}$ such that $a_i a_{i+1} \in g$ for all $i \in \{0, \ldots, p-1\}$. A *component* $C(g)$ in the graph $g$ is a subgraph such that there is a path between any pair of agents in the component, and there is no link in the graph $g$ between any agent inside the component and any agent outside the component. We shall denote $i \in C(g)$ when agent $i$ belongs to component $C(g)$. Finally, $L(C(g))$ will represent the set of links in the component $C(g)$. For clarity and when there are no confusions, we shall omit the argument $g$ from the main symbols: $\mu$, $C$, $A$.

**Technologies and spillovers.** We assume positive marginal cost and no fixed cost. Individual marginal costs are decreasing functions $c_i(\mu_i(g))$ in the number of alliances in which firms are involved. The function is assumed to be linear with slope $-\gamma$ (linearity is crucial for obtaining uniqueness of stable networks). Involuntary spillovers may arise in the industry. When firms $i$ and $j$ engage in a common R&D effort, other firms benefit from marginal cost reduction, by the amount $\rho \in [0, \gamma]$. We denote by $\tau$ the ratio $\frac{\rho}{\gamma}$. When spillovers spread in the whole population (resp. a strict subset), we shall talk about *global* (resp. *local*) spillovers.

**The two-stage game.** In the first stage, firms simultaneously raise collaborative links. Throughout the rest of the paper, we assume that forming links is non costly. We apply the standard stability criterion of pairwise stability, adapted from Jackson and Wolinsky (1996): (i) for $ij \in g$, $\pi_i(g) > \pi_i(g - ij)$ and $\pi_j(g) > \pi_j(g - ij)$, (ii) for $ij \notin g$, if $\pi_i(g + ij) > \pi_i(g)$, then $\pi_j(g+ij) \leq \pi_j(g)$. Once alliances are formed, firms compete with each other in order to maximize individual profits. Given a network $g$, we denote by $\pi_i(g)$ the profit made by firm $i$ on this network. In that specific case, each firm produces some homogenous good, sold at price $p_i$ and in quantity $q_i$. The linear inverse demand schedule is given by $p_i = \alpha - q_i - \sum_{j \neq i} q_j$ in the region where the price is positive, with $\alpha > 0$ measuring the absolute size of the market.

**Network architectures.** The empty (resp. complete, denoted $g^c$) network is the graph such that no pair (resp. every pair) of agents forms a link. The class $g_k$, with $k \in \{\frac{n}{2}+1, \cdots, n-1\}$ if $n$ is even and with $k \in \{\frac{n-1}{2} + 1, \cdots, n-1\}$ if $n$ is odd, denotes a network containing two complete components, the greatest being of size $k$. We also present networks with incomplete components. We first remark that a network $g$ can always be decomposed as follows: partition $g$ into a set of disjoint complete subgraphs $A_1(g), \cdots, A_p(g)$ such that $\sum_{i \leq p} |A_i| = n$. This set is said *minimal* when there is no partition with less elements. Then we can build the graph $g$ as considering the collection $\{A_i\}_{i \in \{1, \cdots, p\}}$ and completing the residual links between the sets. When possible and for convenience, we shall abuse the notation by writing $g = \{A_i\}_{i \in \{1, \cdots, p\}}$ (the notation gives no precision about the links between agents in distinct subgraphs). We denote by $\Gamma(q, \alpha)$ the component architecture such that (i) it contains $(\alpha+1)q$ agents, $\alpha \geq 2$ being an integer, (ii) the component is minimally partitioned into two distinct complete subgraphs $\{A_1, A_2\}$ with $|A_2| = q \geq 2$, (iii) $\mu_k = (\alpha+1)q - 2$ for any $k \in A_1$ (so agents in $A_1$ have $q-1$ partners in $A_2$), (iv) $\mu_i = (\alpha+1)(q-1)$ for any $i \in A_2$. Note that every agent in any complete subgraph has the same number of partners, whereas two agents in two distinct complete subgraphs do not. Hence, the component $\Gamma(q, \alpha)$ contains two complete subgraphs and every agent in the greatest complete subgraph forms connections with all agents less one in the smallest complete subgraph. Further, the organization of links between the two subgraphs is such that any two agents in a given complete subgraph have the same number of partners (see figure 1).

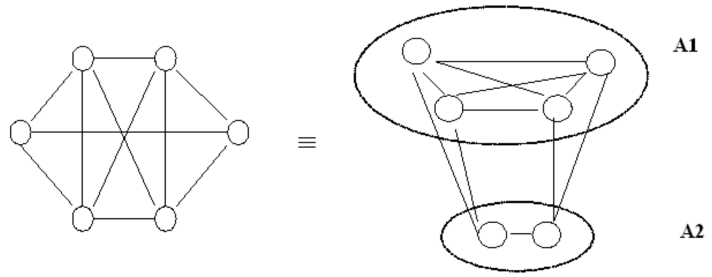


Figure 1: $n = 6$; the network architecture $\Gamma(2, 2)$

We generalize this class to $r \geq 2$ complete subgraphs as follows: we denote by the class $\Gamma(q, \alpha_1, \cdots, \alpha_{r-1})$ the component architecture, containing $(\sum_{i=1}^{r-1} \alpha_i + 1)q$ agents, minimally partitioned into $r$ complete subgraphs $\{A_i\}_{i=1,\cdots,r}$, with $|A_r| = q$, $|A_i| = \alpha_i |A_{i+1}|$, $\alpha_i \geq 2$ being an integer, and such that:

$$\begin{cases} \text{for all } j \in \{1, \cdots, r\}, \text{ for all } i, i' \in A_j,\ ii' \in g \text{ and } \mu_i = \mu_{i'} \\ \text{for all } i, j, i < j,\ \forall k \in A_i,\ |N_k(g) \cap A_j| = |A_j| - 1 \\ \text{for all } i, j \text{ such that } \mu_j < \mu_i \text{ and } ij \notin g, \text{ then } v_{ij} = \mu_j \end{cases}$$

Notably, considering two agents in two distinct complete subgraphs, the agent in the largest subgraph forms a link with all agents less one in the other subgraph; also, for any pair of agents with different number of partners and not forming a link, the set of partners of the less connected agent belongs to the set of partners of the other agent. To finish, we denote by $\Gamma'(q, \alpha_1, \cdots, \alpha_{r-1})$ the class of graphs with $n = (1 + \sum_{i=1}^{r-1} \alpha_i)q + 1$ agents and consisting in the union of one isolated agent and one component $\Gamma(q, \alpha_1, \cdots, \alpha_{r-1})$.

## 3 Results

We examine the stability of strategic networks when spillovers disseminate through the graph of alliances. Beforehand, we present the benchmark case where each new alliance affects the marginal costs of the whole population of agents, *i.e.* generates global spillovers.

### 3.1 Global spillovers

A well-known property of the Cournot oligopoly with linear demand (see Yi [1998]) states that a simultaneous symmetric (favorable) shock on all marginal costs induces positive individual quantity variations in Cournot equilibrium. Then basically:

**Result 3.1** *Under global spillovers, the complete network is uniquely stable.*

(Proof omitted as resulting from Yi [1998])

### 3.2 Neighbor-restricted spillovers

In this case, the marginal cost of agent $i$ in the graph $g$ writes:

$$c_i(g) = c_0 - \gamma\mu_i(g) - \rho \sum_{j \in N_i(g)} \sum_{k \in N_j(g) \setminus N_i(g)} \mu_k(g)$$

**Proposition 3.1** *Suppose that spillovers are neighbor-restricted. Then, the set of possibly stable architectures is reduced to the complete network, the network $g_{n-1}$, and some networks in the classes $\Gamma(\alpha_1, \cdots, \alpha_{r-1})$ and $\Gamma'(\alpha_1, \cdots, \alpha_{r-1})$, $r \geq 2$. Furthermore,*
*(i) $\{g^c\}$ is stable for any $\tau \in [0,1]$,*
*(ii) $\{g^{n-1}\}$ is stable for any $\tau \in \left[\frac{n-1}{2(n-2)}, 1\right]$,*
*(iii) the class $\{\Gamma(q,\alpha)\}$ is stable for any $\tau \geq \frac{n-1}{n-3+\alpha}$,*
*(iii') the class $\{\Gamma'(q,\alpha)\}$ is stable for any $\tau \geq \max\left[\frac{n-1}{n-3+\alpha}, \frac{q}{2(q-1)}\right]$,*
*(iv) other stable networks exist in the classes $\Gamma(\{\alpha_i\}_{i=1,\cdots,r-1})$ and $\Gamma'(\{\alpha_i\}_{i=1,\cdots,r-1})$, $r \geq 3$ (under conditions given in the proof).*

Let us present a stable incomplete network $g$ with 3 minimally complete subgraphs defined as follows: $g = \{A_1, A_2, A_3\}$, with $|A_1| = \alpha|A_2| = \alpha\beta|A_3|$ ($\alpha, \beta \geq 2$ and integers), $|A_3| \geq 2$. By definition, $\mu_k = n-3$ for all $k \in A_1$, $\mu_j = n - \alpha - 2$ for all $j \in A_2$, $\mu_i = n - (\alpha+1)\beta - 1$ for all $i \in A_3$. The graph is stable if $\tau \geq \max\left[\frac{n-1}{n-4+\alpha}, \frac{n-1}{n-1+(\beta-2)(\alpha+1)}\right]$. Hence, if $\alpha = 2$, the graph is always instable; if $\alpha = 3$, the graph is stable for $\tau = 1$; if $\alpha \geq 4$, the graph is stable for any $\tau \geq \frac{n-1}{n-4+\alpha}$ as soon as $\beta \geq \frac{3\alpha-1}{\alpha+1}$.

**Remark 3.1.1.** In the case $n = 3$, if $g^0$ denotes the graph with one link, $S = \{g^c\}$ for any $\tau \in [0,1[$ and $S = \{g^c, g^0\}$ when $\tau = 1$. If $n \in \{4,5\}$, $S = \{g^c\}$ for any $\tau \in [0,1]$. If

$n = 6$, denote $\tilde{g}$ as the graph depicted in the figure 1. Then $S = \{g^c\}$ for any $\tau \in [0, 1[$ and $S = \{g^c, \tilde{g}\}$ as $\tau = 1$.

**Remark 3.1.2.** Some moderate level of asymmetry applies. For instance, the following claim indicates that an incomplete component does not contain one agent that would be linked to all other agents:

**Claim 3.1** *Suppose that $n \geq 3$ and that a stable graph $g$ contains one incomplete component $C$. Then, no agent in the component has $|C| - 1$ partners.*

This moderate asymmetry mainly stems from two properties possessed by stable networks:

***(P1)*** *Suppose that a stable graph $g$ contains one incomplete component $C$. Then for every pair of agents $(i, j)$ in the component $C$ such that the link $ij \notin g$, $\mu_i \neq \mu_j$.*

***(P2)*** *A stable graph $g$ with $ik \notin g$ and $\mu_k > \mu_i$ must satisfy $v_{ik} = \mu_i$.*

By property *(P1)* if two agents do not form a connection, they do not have the same number of partners. Property *(P2)* states that if two agents who do not form a link in a stable graph have a distinct number of partners, then all the partners of the agent having the least number of partners are also partners of the other. The former property favors asymmetric networks, whereas the latter ensures some minimal overlapping between asymmetrically positioned agents.

**Remark 3.1.3.** When the inverse demand is concave, a major implication is that the condition of link formation profitability becomes dependent on equilibrium quantities[2].

**Remark 3.1.4.** The set efficient networks, defined as the sum of aggregate surplus and consumer surplus, is reduced to the complete network. The proof is formally identical to Goyal and Joshi (2003, 2004). Indeed, one just have to recall that $c_i(g) > c_i(g^c)$ whenever $g \neq g^c$; for that, note that, in the complete network, for each agent the number of direct alliances as well as partners' partners are maximized. Hence, part of stable networks are under-connected with respect to social welfare.

[2] Indeed, straightforward comparative statics at equilibrium indicate that (i) when $P'(Q)$ is decreasing then the equilibrium total demand $Q$ increases, and (ii) a favorable cost shock on a subset $K$ of firms, denoted $dC^k = \sum_{k \in K} dc_k$, entails positive profit for firm $i$ if $\frac{|dc_i|}{|dC^k_{-i}|} > \frac{1+Rq_i}{n+RQ_{-i}}$, where $R = \frac{P"(Q)}{P'(Q)}$, $dC^k_{-i} = dC^k - dc_i$ and $Q_{-i} = Q - q_i$. Denoting $H_i = \frac{1+Rq_i}{n+RQ_{-i}}$, $H_i < \frac{1}{n}$ iff $q_i > \frac{Q}{n+1}$ (assuming $R > 0$). A link is profitable for the two involved agents $i, j$ whenever $\mu_i < f_i(\mu_j)$ and $\mu_j < f_j(\mu_i)$, with $f_i(x) = \left[\frac{n-1+R(Q-2q_i)}{2+2Rq_i}\right]\left(\frac{1}{\tau} + \mu_j - v_{ij}\right)$. Hence, the greater the equilibrium quantity $q_i$, the smaller agent $i$ 's incentive to form a new link.

### 3.3 Component-restricted spillovers

In this case, the marginal cost of agent $i$ in the graph $g$ writes:

$$c_i(g) = c_0 - \gamma\mu_i(g) - \rho\big[|L\big(C_i(g)\big)| - \mu_i(g)\big]$$

Another form of moderate asymmetry is detected.

**Proposition 3.2** *Suppose that spillovers are component-restricted. Then:*
*(i) stable networks are the union of complete components of distinct size,*
*(ii) the incentive of link formation in a given complete component is non-monotonic (decreasing then increasing) with respect to the size of the partner's component.*

The figure 2 illustrates the non-monotonicity of the result. The curve describes the critical values $\tau_k$ associated with each graph $g_k$ in the case $n = 17$. For a given value of $k$, the graph $g_k$ is stable if $\tau \geq \tau_k$.

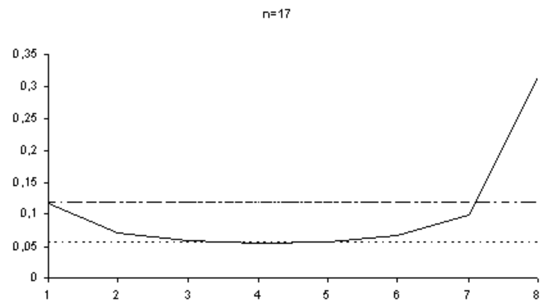


Figure 2: Non monotonicity of stable graphs $g_k$ with respect to $\tau$; X-axis=k, Y-axis=$\tau_k$

This result is easily interpreted. When considering two agents in two distinct complete components, the agent in the greatest one is the less interested by the alliance. When her potential partner is in a very small component, her incentive to form a link decreases with the size of the partner's component since more agents shall receive spillovers from her own component. On the opposite, when the size of the partner's component is sufficiently large, she can expect receiving a more substantial amount of spillovers from the other component, which finishes to dominate the negative incentive.

**Remark 3.2.1.** Examples of stable graphs with 3 complete components: the smallest population size entailing stability of three components for $\tau = 1$ is $n = 10$ and the triplet $(1, 4, 5)$

is stable (each number in the triplet denotes the size of a complete component). To find a stable network with four components we must reach the size $n = 55$, and we find $(1, 10, 19, 25)$ as being stable. Five stable components requires to go around $n = 2000$. For instance, the network $(1, 63, 324, 659, 953)$ is easily seen to be stable (see the end of the appendix for an illustration of how checking that a network containing complete components is stable).

**Remark 3.2.2.** Two components of size less than $\frac{n}{2}$ may not coalesce (if their sizes are sufficiently different, the agent in the largest component shall not find the link profitable - see in the appendix the lemma 4.3 and the illustration given after the proof of the proposition 3.2).

**Remark 3.2.3.** The proposition also applies for smoothly concave inverse-demand function. Furthermore, like in the preceding subsection, 'convexification' of demand makes profitability depend on quantities[3].

**Remark 3.2.4.** Like in the preceding subsection, the unique efficient network is the complete network.

# 4 Appendix

**Proof of proposition 3.1.**

*Profitability of link formation:* in homogenous Cournot oligopoly with linear demand, equilibrium quantity of firm $i$ writes $q_i = \frac{\alpha - nc_i + \sum_{j \neq i} c_j}{n+1}$. Consider a non complete graph $g$ and one link $ij \notin g$. Then, the equilibrium quantity in the graph $g + ij$ writes:

$$q_i(g+ij) = \frac{\alpha - n(c_i(g) - \gamma - \rho(\mu_j - v_{ij})) + c_j(g) - \gamma - \rho(\mu_i - v_{ij}) + \sum_{k \neq i,j} c_k - \rho(\mu_i(g) + \mu_j(g) - v_{ij})}{n+1}$$

[3] Hence, a link is profitable for the two involved agents $i, j$ whenever $\zeta_i < f_i(\zeta_j)$ and $\zeta_j < f_j(\zeta_i)$, with

$$f_i(x) = 1 - \frac{x}{2} - \frac{1}{x} + \frac{1}{2}\sqrt{\left(x - 2 + \frac{2}{x}\right)^2 - 4\left(\frac{1}{H_i} + n - 1\right)\left[\frac{2}{\tau}\left(\frac{1}{H_i} - 1\right) - 2(n-2)\right]}$$

When $H_i$ increases, the function increases so that the unique positive root of $f(x) - x$ increases. As a consequence, when the inverse-demand function is concave, if $q_i < q_j < \frac{Q}{n+1}$, then $H_i < H_j < \frac{1}{n}$ and the condition of link formation profitability is more restrictive than under linear demand; when $q_i > q_j > \frac{Q}{n+1}$, then $H_i > H_j > \frac{1}{n}$ and the condition is less restrictive; when $q_i < \frac{Q}{n+1} < q_j$, then $H_i < \frac{1}{n} < H_j$ and the condition is more (resp. less) restrictive for agent $i$ (resp. agent $j$).

so that:

$$q_i(g+ij) - q_i(g) > 0 \text{ iff } \mu_i < \frac{n-1}{2\tau} + \frac{n-2}{2}(\mu_j - v_{ij}) + \frac{\mu_j}{2}$$

The link is formed if this relation is true simultaneously for agents $i$ and $j$ (substituting labels $i$ and $j$ in this above inequality). Denote $f_\tau(\mu_j, v_{ij}) = \frac{n-1}{2\tau} + \frac{n-2}{2}(\mu_j - v_{ij}) + \frac{\mu_j}{2}$. We note that $f_\tau$ is decreasing *w.r.t.* both parameter $\tau$ and argument $v_{ij}$. Hence, the condition under which the link formation is profitable is more restrictive when $\tau$ and $v_{ij}$ attain their maximum value.

Thus, points (i) and (ii) of the proposition are checked directly by direct inspection. Concerning the points (iii), (iii') and (iv), we need first to use the following lemma:

**Lemma 4.1** *A stable network contains either one component or two components with one being an isolated agent.*

**Proof.** Suppose that a stable network $g$ contains two components. Consider two agents $i$ and $j$ in each. Then $v_{ij} = 0$. The link $ij$ is profitable for agent $i$ if $\mu_i < \frac{n-1}{2}\left(\frac{1}{\tau} + \mu_j\right)$. Note that if $\mu_j \geq 1$ the condition is automatically satisfied. Then a stable network with two components contains at most one isolated agent. To finish, check that two distinct isolated agents have an incentive to form a link. □

The lemma strongly restricts the set of stable architectures. Second, we focus on stable networks with incomplete components and show uniqueness of the classes $\Gamma$ and $\Gamma'$, by remarking two properties:

***Property (P1)*** *Suppose that a stable graph $g$ contains one incomplete component $C$. Then for every pair of agents $(i,j)$ in the component $C$ such that the link $ij \notin g$, $\mu_i \neq \mu_j$.*

**Proof.** Suppose that $\mu_i = \mu_j = \mu$ and that the link $ij$ is not profitable. The required condition writes $\mu \geq \frac{n-1}{2\tau} + \frac{(n-1)\mu}{2} - \frac{(n-2)v_{ij}}{2}$, that is $n-1 \leq (n-2)v_{ij} - (n-3)\mu$. The right hand side is increasing in $v_{ij}$ and in the case $v_{ij} = \mu$, we obtain $n-1 \leq \mu$, which is impossible. □

***Property (P2)*** *A stable graph $g$ with $ik \notin g$ and $\mu_k > \mu_i$ must satisfy $v_{ik} = \mu_i$.*

**Proof.** We must have $\mu_k \geq \frac{n-1}{2\tau} + \frac{\mu_i}{2} + \frac{n-2}{2}(\mu_i - v_{ik})$. If $\mu_i - v_{ik} \geq 1$, this is impossible for all admissible value of $\tau$. □

Properties *(P1)* and *(P2)* jointly ensure that some incomplete component in a stable network belongs to the class $\Gamma(q, \alpha_1, \cdots, \alpha_{r-1})$.

Point (iii):

**Lemma 4.2** *Suppose that a stable graph contains one component $C$, with $C$ minimally partitioned into two complete subgraphs $A_1, A_2$, and $|A_2| = q < |A_1|$. Then, (i) if $\frac{n-q}{q}$ is not an integer the graph is instable, (ii) if $n - q = \alpha q$, $\alpha$ being an integer, then the component is in the class $\Gamma(q, \alpha)$ and one needs $\tau \geq \frac{n-1}{n-3+\alpha}$.*

**Proof.** (i) if $\frac{n-q}{q}$ is not an integer, then it is not possible to get property *(P1)*. Indeed, from *(P1)* it stems that if two distinct agents in a stable graph $g$ have the same number of links, then they form a link in $g$. This leads to the building up of complete subgroups of agents having all the same number of partners. Hence, if the component $C$ is incomplete, the component can be minimally partitioned into at least two complete subgraphs. We suppose here that there are two minimally complete subgraphs. If agents in $A_i$ have the same number of partners, this means that they have the same number of partners *outside* $A_i$. But this is not possible to fix $\frac{|A_1|}{|A_2|}$ as not integer and to have that any agent in $A_2$ has the same number of partners in $A_1$.

(ii) the result basically follows from property *(P2)*. Indeed, as $A_2$ is a complete subgraph, the property implies that any agent in $A_1$ has $q - 1$ partners in $A_2$. The conditions for stability of the class is the following. Given that $|A_2| = q$ and $|A_1| = \alpha q$, $\mu_k = n - 2$ for all $k \in A_1$ and $\mu_j = (1 + \alpha)(q - 1)$ for all $j \in A_2$. Since $v_{ik} = \mu_i$, forming the link is not profitable to agent $k$ if $\tau \geq \frac{n-1}{n-3+\alpha}$. Hence the constraints define exactly the class $\Gamma(q, \alpha)$. $\square$

Point (iii'): for the class $\Gamma'(q, \alpha)$ to be stable, we need more. Consider agent $j \in A_2$, $k \in A_1$ (where $A_1$ and $A_2$ are the two subgraphs of the component $\Gamma$) and denote by $l$ the isolated agent. In addition to the conditions of the lemma just above, if agent $j$ has not interest to form the link $jl$, then the graph is stable ($\mu_j < \mu_k$ so the constraint on the link $jl$ is stronger than the constraint on the link $kl$). But agent $j$ has not interest to form the link $jl$ if $\mu_j \geq \frac{n-1}{2\tau}$. Replacing $\mu_j$ by its value $(q-1)(1+\alpha)$ and noting that $n - 1 = q(\alpha + 1)$ this entails $\tau \geq \frac{q}{2(q-1)}$ (Note that, given that $n - 1 = (\alpha + 1)q$, $\frac{n-1}{n-3+\alpha} < \frac{q}{2(q-1)}$ iff $q < \frac{3\alpha}{\alpha+1}$).

Point (iv):

**Lemma 4.3** *Suppose that a stable graph contains one component $C$, with $C$ minimally partitioned into $r$ complete subgraphs $A_1, \cdots, A_r$, and $|A_i| = \alpha_i |A_{i+1}|$. Then the stable graphs are built as follows: (i) $A_i$ is a complete subgraph, (ii) for all $(i,j) \in A_i \times A_j$, $j > i$, then agent $i$ forms a link with $|A_j| - 1$ agents in $A_j$, (iii) for all $(i,j) \in A_i \times A_j$, $j > i$, then $v_{ij} = \mu_j$, (iv) $\tau \geq \max_{(j,k)/\mu_j < \mu_k} \left[ \frac{n-1}{2\mu_k - \mu_j} \right]$.*

(The proof is omitted, replicating directly the above one - using properties *P1* and *P2*.) The point (iv) follows directly: the class $\Gamma(q, \alpha_1, \cdots, \alpha_{r-1})$ is stable under the requirement on $\tau$ given in the lemma; the stability of the class $\Gamma'(q, \alpha_1, \cdots, \alpha_{r-1})$ requires the additional condition $\tau \geq \frac{q}{2(q-1)}$. To finish, uniqueness is ensured by recalling to mind the lemma 4.1. ■

**Proof of the claim 3.1.** Consider a stable graph $g$ with an incomplete component; consider, in this component, three agents $i$, $j$ and $k$ such that $ij \in g$, $ik \notin g$ and without loss $\mu_k > \mu_i$. Straightforward computations show that $\mu_k > \mu_j - \frac{1}{2} + \frac{n-2}{2} \Big( 1 + v_{ij}(g - ij) - v_{ik}(g) \Big)$. Suppose that $\mu_j = |C| - 1$: then $v_{ij}(g - ij) = \mu_i - 1$, entailing $\mu_k > n - \frac{3}{2} + \frac{n-2}{2} \Big( \mu_i - v_{ik}(g) \Big)$. Since $v_{ik}(g) \leq \mu_i$, this is not possible. □

**Proof of proposition 3.2.** Point (i):

*In a stable graph, components are complete; stability of the complete network:* consider a non complete graph $g$ and suppose that there exists a component containing two agents $i$ and $j$ such that $ij \notin g$. Then we see immediately that these two agents have an incentive to form a link. Indeed, we are replaced in a game similar to the case of global spillovers, since forming a link induces spillovers to the other agents of the component, but agent $i$ (resp. agent $j$) does not receive spillovers from agent $j$'s component (resp. agent $i$'s component) as they already belong to the same one. Hence, following Yi (1998), it basically stems that the component is complete. Further, we deduce that the complete network is stable for all values of $\tau \in [0, 1]$.

*Profitability of link formation between two distinct complete components:* consider a network $g$ containing two distinct complete components, and two agents $i$ and $j$ taken from two distinct components. Let us denote the size of (resp. the number of links in) agent $i$'s component as $\zeta_i$ (resp. $L_i$). We compute the equilibrium quantity variation of agent $i$ when the alliance $ij$ is formed as follows:

$$q_i(g+ij) - q_i(g) = \frac{n(\gamma + \rho L_j) - (\gamma + \rho L_i) - (\zeta_i - 1)\rho(L_j + 1) - (\zeta_j - 1)\rho(L_i + 1)}{n+1}$$

That is, as replacing $L$ by $\frac{\zeta(\zeta-1)}{2}$:

$$q_i(g+ij) - q_i(g) > 0 \text{ iff } \zeta_i^2 + \left(\frac{2}{\zeta_j} + \zeta_j - 2\right)\zeta_i - \left[\frac{2(n-1)}{\tau\zeta_j} + (n+1)(\zeta_j - 1) - 2\frac{\zeta_j - 2}{\zeta_j}\right] < 0$$

This order-2 polynomial admits two roots of opposite sign. Hence, it is profitable for both agents $i$ and $j$ to form an alliance with each other when $\zeta_i < f(\zeta_j)$ and $\zeta_j < f(\zeta_i)$, with

$$f_\tau(x) = 1 - \frac{x}{2} - \frac{1}{x} + \frac{1}{2}\sqrt{\left(x - 2 + \frac{2}{x}\right)^2 + 4(n+1)(x-1) + \frac{8(n-1)}{\tau x} - \frac{8(x-2)}{x}}$$

*In a stable graph, two components cannot have equal size:* we know from the above analysis that in stable networks components are complete. Consider two agents $i$ and $j$ of distinct complete components with equal size $\zeta$. From above we note that the link is profitable iff $\zeta < f_\tau(\zeta)$, *i.e.* $-2\zeta^3 + (n+3)\zeta^2 - (n+5)\zeta + \frac{2(n-1)}{\tau} + 4 > 0$. We define the function $g_\tau(x) = -2x^3 + (n+3)x^2 - (n+5)x + \frac{2(n-1)}{\tau} + 4$, for $x \in \{1, \cdots, \frac{n}{2}\}$ if $n$ is even and for $x \in \{1, \cdots, \frac{n-1}{2}\}$ if $n$ is odd. First we observe that for all values of $x$, $g_\tau(x)$ is decreasing with parameter $\tau$. So, in order to show that the function is positive for all $x \leq \frac{n}{2}$, it is sufficient to consider the case $\tau = 1$. We easily see that $g_1(0) > 0$, $g_1(+\infty) = -\infty$, $g_1'(0) < 0$ and $g_1''(x) \leq 0 \Leftrightarrow x \geq \frac{n+3}{6}$ when $x > 0$. We deduce that this order-3 polynomial $g_1(.)$ admits a unique positive root, and the polynomial is positive (resp. negative) for any positive value of $x$ smaller (resp. greater) than this root. To finish, we see that for $n$ even, $g_1(\frac{n}{2}) > 0$ and for $n$ odd, $g_1(\frac{n+1}{2}) > 0$. If $n$ is even, $g_1(\frac{n}{2}) = \frac{n^2-2n+8}{4}$, which is positive. If $n$ is odd, $g_1(\frac{n+1}{2}) = 0$. Hence, the root is beyond half of the population. This means that two agents belonging to two distinct complete components of equal size have always an incentive to form a link.

Point (ii): let us define the function $h_\tau(x,y) = \frac{2(n-1)}{\tau} + (n+1)y(y-1) - (xy+2)(x+y-2)$, with $x \in \{1, \cdots, n-1\}$ and $y \in \{1, \cdots, n-x\}$. Then $h_\tau(\zeta_i, \zeta_j) = (n+1)\big(q_i(g+ij) - q_i(g)\big)$. For any $\tau \in [0,1]$, note that (1) if $1 \leq y < x$, $h_\tau(x,y) < h_\tau(y,x)$: the agent in the greatest complete component has always less incentive to form a link than the other. (2) $\forall x > 0$, $h_\tau(x+1,y) < h_\tau(x,y)$: when the size of the complete component of some agent increases, the agent has less incentive to form a link with some agent in a component of fixed size. (3)

$h_\tau(x, y+1) - h_\tau(x, y) > 0$ iff $y > \frac{x^2-x+2}{2(n+1-x)}$: the incentive of link formation of some agent in a given complete component is non-monotonic (decreasing then increasing) with respect to the size of the partner's component. ■

Let us say more concerning bounds on the sizes of stable components: the solution $x^*_\tau$ of the equation $x = f_\tau(x)$ is also the root of $g_\tau(x)$, which has been seen to be greater than half the population. From the following basic lemma we will deduce that for two distinct components to be stable the difference in their size must be large enough:

**Lemma 4.4** *Consider a function $t$ with real argument in $[1, +\infty)$, such that $t$ is continuous, differentiable with continuous derivative, strictly increasing, $t(x) = x$ admits a unique solution $x^*$ and $t'(x^*) < 1$. Then, (i) for any $y > x^*$, if $x < t(y)$, then $y > t(x)$, (ii) for any $y \in ]t(1), x^*[$, there exists $t^{-1}(y) > 0$ such that for all $x \in ]t^{-1}(y), y[$ (resp. $x < t^{-1}(y)$), then $x < t(y)$ and $y < t(x)$ (resp. $x < t(y)$ and $y > t(x)$).*

The function $f_1$ defined above is increasing and satisfies the conditions of the lemma. Part (i) entails that one does not have simultaneously $\zeta_i < f_1(\zeta_j)$ and $\zeta_j < f_1(\zeta_i)$ as soon as $max(\zeta_i, \zeta_j) > x^*_1$. Part (ii) implies that two distinct components of size less than $x^*_1$ may coexist in a stable graph if their sizes are not too much close. Note that, when $\tau$ increases the constraint is relaxed, so that whatever $\tau_a < \tau_b$, whatever stable graph $g_a$ for $\tau_a$ there exists a stable graph $g_b$ for $\tau_b$ such that $g_a$ is a subgraph of $g_b$ (even if function $f$ does not satisfies the conditions of the lemma for $\tau < 1$). This means that any stable network for $\tau < 1$ is also a union of complete components. We give a simple illustration of how checking that a network composed of complete components is or is not stable, in the case $n = 10$ and $\tau = 1$ (this is the minimum network size generating a stable union of three complete components):

| y | $x_1^*(y)$ |
|---|---|
| 1 | **4** |
| 2 | **4** |
| 3 | **4.4** |
| 4 | **4.9** |
| 5 | **5.3** |

| | | | | | | |
|---|---|---|---|---|---|---|
| 5 | | | | | **unstable** | |
| 4 | | | | **unstable** | **stable** | **stable** |
| 3 | | | **unstable** | **unstable** | **stable** | **stable** |
| 2 | | **unstable** | **unstable** | **stable** | **stable** | **stable** |
| 1 | **unstable** | **unstable** | **unstable** | **stable** | **stable** | **stable** |
| | 1 | 2 | 3 | 4 | 5 | 6 |

Table 1: $n = 10$, $\tau = 1$

The left-hand table represents, for two components of size $y$ and $x$, $y \leq x$, the maximum size $x^*_1(y)$ below which two agents belonging to the respective components find profitable to form a link. The condition examines the link formation profitability of the agent in the greatest component -the less incited-; for instance the line $y = 3, x_1^*(3) = 4.4$ should be interpreted as 'an agent in a component of size 4 (resp. 5 or more) finds profitable (resp. not profitable) to form a link with some agent in a component of size 3'. This makes possible to determine which potential link would be profitable for both parties, as summarized in the right-hand table: coordinates represent component sizes, with the convention that the size $x$ is on the X-axis and the size $y$ ($\leq x$) on the Y-axis; when the link is profitable (resp. not profitable) to both partners, the word 'unstable' (resp. 'stable') is used. We check that $S = \{(1,4,5), g_6, g_7, g_8, g_9, g^c\}$, where $(1,4,5)$ denotes the network composed of three complete components of size 1, 4 and 5.

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(lxv) This paper was presented at the EuroConference on “Auctions and Market Design: Theory, Evidence and Applications” organised by Fondazione Eni Enrico Mattei and sponsored by the EU, Milan, September 25-27, 2003

(lxvi) This paper has been presented at the 4th BioEcon Workshop on “Economic Analysis of Policies for Biodiversity Conservation” organised on behalf of the BIOECON Network by Fondazione Eni Enrico Mattei, Venice International University (VIU) and University College London (UCL) , Venice, August 28-29, 2003

(lxvii) This paper has been presented at the international conference on “Tourism and Sustainable Economic Development – Macro and Micro Economic Issues” jointly organised by CRENoS (Università di Cagliari e Sassari, Italy) and Fondazione Eni Enrico Mattei, and supported by the World Bank, Sardinia, September 19-20, 2003

(lxviii) This paper was presented at the ENGIME Workshop on “Governance and Policies in Multicultural Cities”, Rome, June 5-6, 2003

(lxix) This paper was presented at the Fourth EEP Plenary Workshop and EEP Conference “The Future of Climate Policy”, Cagliari, Italy, 27-28 March 2003

(lxx) This paper was presented at the 9$^{th}$ Coalition Theory Workshop on "Collective Decisions and Institutional Design" organised by the Universitat Autònoma de Barcelona and held in Barcelona, Spain, January 30-31, 2004

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