2 When in a pair-wise stable network, $\max_{l=1,2,\dots,p}\{m(g_l)\} > \bar{m}^* + 1$, *this largest component is not fully interconnected. Moreover, if there exist more than one component, they might not be complete and their sizes could be equal to the size of the largest component. Components whose sizes are greater than* $\bar{m}^* + 1$ *are not complete and their members will have* $\bar{m}^*$ *agreements. On the contrary, components whose sizes are smaller or equal to* $\bar{m}^* + 1$ *are fully interconnected with different sizes and their members will have at most* $\bar{m}^*$ *agreements.*

Item 2 of this proposition shows a contrasting result with that of 1. In particular, it shows that a subset of $\mathcal{G}$ is composed of not fully interconnected symmetric components. The following propositions charactherize further the nature of collusive networks. In particular:

Proposition 6 (Ineffective Antitrust Policy)**.** *The complete network* $g^c \in \mathcal{G}^*$ *if, and only if,*

$$\big(1-\gamma(2)\big)^{n-2}\Big(1-\gamma(1)\big)^2 - \big(1-\gamma(2)\Big).$$

Similarly, at the other extreme:

Proposition 7 (Effective Antitrust Policy)**.** *Let* $\underline{n}^* = n$. *Then the empty network is the unique pair-wise stable network.*

5. Discussion and Concluding Remarks

This article has studied the set of collusive stable networks under two different policy frameworks. Naturally, the presence of an antitrust policy weakens firm's incentives to participate in collusive agreements since it reduces the net expected benefit from signing them. In the current network framework, the channels through which antitrust policy impacts on competition has its peculiarities. Firms, considering whether or not to sign an agreement, take into account the probability of being discovered rather than the probability of being inspected, and the first probability positively depends on the number of agreements that each firm has signed.

In one of our cases, the probability of inspection is constant and the penalty imposed by the authority is equal to the total profits of a guilty firm. In such a case, that penalty depends on the network configuration as a whole. On the other hand, in the other case being studied, the probability of inspection depend on the network configuration but the penalty imposed by the authority is fixed.

For the first case, we have shown that pair-wise stable networks can be decomposed into a set of isolated firms and complete components of different sizes. Moreover, we concluded that, when the authority set a fixed and sufficiently small probability of inspection, the complete network is pair-wise stable. But as the authority increases γ, are smaller alliances the first to be destroyed or detected. In turn, the set of isolated firms expands. Therefore, as γ increases, the empty network, g^e, tends to emerge as the only pair-wise stable network. Recalling that in an empty network, all firms are active in all markets, we conclude that this policy has pro-competitive effects.

On the other hand, when the authority reacts to costumers' complains, i.e., when γ depends on n, components are not necessary complete in pair-wise stable networks. Besides, it is possible to define a lower bound on the size of components. This bound is related with the number of isolated firms and it has important impacts on the level of competition in the market. As the minimal number of firms active in a market that are necessary for make an agreement profitable increases, it is possible to expect more competitive structure.

An important policy implication of the present formulation is that the organization of the illegal behavior matters. That is, the analysis of the optimal deterrence of market-sharing agreements has to take into account the organizational structure of collusive firms. Furthermore, without considering the effects of the organizational structure, empirical studies may overestimate the contribution of efforts devoted to investigate and prosecute collusive agreements.[8] Finally, determining the optimal antitrust policy in a network context is part of our agenda for future research.

A. Proofs

Proof of Lemma 1. Recall that

$$M_i(n_i, n_j, n_k, \gamma) := \pi(n_i - 1) - \pi(n_i) - \pi(n_j) - \gamma\big(\pi(n_i - 1) + \sum_{k \neq j, a_{ik}=0} \pi(n_k)\big).$$

To save on notation we write $M_i \equiv M_i(n_i, n_j, n_k, \gamma)$. Then: (a) Since by A1 $\pi(.)$ is a decreasing function, an increase in n_j decreases $\pi(n_j)$ and hence it increases M_i; (b) Since by A1 $\pi(.)$ is a decreasing function, an increase in n_k decreases $\sum_{k \neq j, a_{ik}=0} \pi(n_k)$ and hence it increases M_i; (c) An increase in γ clearly diminishes M_i; and (d) From A2 a decrease in n_i increases $\pi(n_i - 1) - \pi(n_i)$ but at the same time it increases $\gamma(\pi(n_i - 1)$. $\square$

Proof of Proposition 1. We first provide necessary conditions. Sufficiency is shown at last.
Necesity: We follow a sequence of steps.
(a) $n_i = n = n_j$. As network g is pairwise stable, when $g_{ij} = 1$ the following two conditions must simultaneously hold

$$\begin{aligned}
(1-\gamma)\pi(n_i - 1) &\geq \pi(n_i) + \pi(n_j) + \gamma \sum_{k: g_{ik}=0} \pi(n_k). \\
(1-\gamma)\pi(n_j - 1) &\geq \pi(n_j) + \pi(n_i) + \gamma \sum_{k: g_{jk}=0} \pi(n_k)
\end{aligned}$$

Given that by A1 $\pi(.)$ is decreasing in n, the following are a pair of necessary conditions that must be satisfied for the above inequalities to hold:

$$\begin{aligned}
\pi(n_i - 1) &> \pi(n_j) \\
\pi(n_j - 1) &> \pi(n_i)
\end{aligned}$$

From the first inequality, $n_i - 1 < n_j$, and from the second one, $n_j - 1 < n_i$. Hence:

$$n_j - 1 < n_i < n_j + 1 \Leftrightarrow n_i = n_j$$

and the result follows.

[8]Some empirical papers that estimate the deterrent effect of the policy are, among others, Buccirossi and Spagnolo,2005; Connor, 2006; Zimmerman and Connor, 2005

(b) **Any component** $g' \in g$ **is complete**. Suppose not. Then, there are three firms i, j, l in the component such that $g_{ij} = g_{jl} = 1$ and $g_{il} = 0$. As g is stable, from part (a) we know that $n_i = n_j \equiv n$ and $n_j = n_l \equiv n$, then $n_i = n_j = n_l \equiv n$. From the stability conditions in part (a) we have that $M_i \geq 0$ for $g_{ij} = 1$:

$$\underbrace{\frac{\pi(n)}{\pi(n+1)}}_{A} \geq \underbrace{\frac{2}{(1-\gamma)} + \frac{\gamma \sum_{k:g_{ik}=0, i\neq k} \pi^i(n_k(g))}{(1-\gamma)\pi(n+1)}}_{B}$$

Similar conditions must hold for the other firms. Given that $g_{il} = 0$ and g' is stable one or both conditions hold for $h = i$ and/or $h = l$:

$$\underbrace{\frac{\pi(n-1)}{\pi(n)}}_{D} < \underbrace{\frac{2}{(1-\gamma)} + \frac{\gamma \sum_{k:g_{hk}=0, h\neq k} \pi^h(n_k(g))}{(1-\gamma)\pi(n)}}_{E}$$

By A2 it follows that

$$A \leq D$$

and from stability

$$B \leq A \leq D < E$$

However, from A1 it is direct to see that:

$$B > E,$$

leading to a contradiction. Therefore g' must be a complete component.

(c) **Components must have different sizes**. Take two firms i, j in component g' and a firm l in g''. Suppose that $m(g') = m(g'')$. Therefore, we have $n_i = n_j = n_l \equiv n$. The stability of g implies that $M_i \geq 0$ and $M_j \geq 0$. Hence:

$$\underbrace{\frac{\pi(n)}{\pi(n+1)}}_{A} \geq \underbrace{\frac{2}{(1-\alpha)} + \frac{\alpha \sum_{k:g_{ik}=0, i\neq k} \pi^i(n_k(g))}{(1-\alpha)\pi(n+1)}}_{B}$$

For $h = i$ and/or $h = l$, the following condition holds:

$$\underbrace{\frac{\pi(n-1)}{\pi(n)}}_{D} < \underbrace{\frac{2}{(1-\alpha)} + \frac{\alpha \sum_{k:g_{hk}=0,\ h\neq k} \pi^i(n_k(g))}{(1-\alpha)\pi(n)}}_{E}$$

By A2

$$A \leq D$$

and since the network is stable

$$B \leq A \leq D < E$$

However, from A1 it is direct to see that:

$$B > E$$

leading to a contradiction.
(d) **Components must have different sizes** Let $i \in g_h^*$ and suppose it does not have incentives to cut a link with a firm inside its component. Then:

$$\frac{\pi\left(N-m\left(g_h^*\right)\right)}{\pi\left(N-m\left(g_h^*\right)+1\right)}>\frac{2}{(1-\gamma)}+\frac{\gamma\left[\left(m\left(g_l\right)+1\right)\pi\left(N-m\left(g_l\right)\right)+\sum_{k:g_{ik}=0}\pi\left(n_k\right)\right]}{(1-\gamma)\,\pi\left(N-m\left(g_h^*\right)+1\right)} \tag{8}$$

Assume however that $j \in g_l$ for $m\left(g_l\right)>m\left(g_h^*\right)$ does have an incentive to cut a link with a firm inside its component. Then:

$$\frac{\pi\left(N-m\left(g_l\right)\right)}{\pi\left(N-m\left(g_l\right)+1\right)}<\frac{2}{(1-\gamma)}+\frac{\gamma\left[\left(m\left(g_h^*\right)+1\right)\pi\left(N-m\left(g_h^*\right)\right)+\sum_{k:g_{jk}=0}\pi\left(n_k\right)\right]}{(1-\gamma)\,\pi\left(N-m\left(g_l\right)+1\right)} \tag{9}$$

Since, by A1 $\pi(.)$ is decreasing in n, it follows that RHS(8)>RHS(9). By A2, the LHS(8)<LHS(9). Therefore, if i does not have an incentive to cut a link with a firm inside its component, LHS(8)>RHS(8), and hence LHS(9)>RHS(9), which contradicts (9).
Sufficiency. Consider a network g that can be decomposed into a set of isolated firms and distinct complete components, g_1,...,g_L of different sizes $m\left(g_l\right) \neq m\left(g_{l'}\right)$,$\forall l, l'$. Isolated players have no incentive to create a link with another isolated one. As long as a firm i, which belongs to the smallest component, does not have incentives to cut a link with a firm inside its component, then, no firm inside a component has incentives to cut a link. Additionally, given that $m\left(g_l\right) \neq m\left(g_{l'}\right)$,$\forall l, l'$, there do not exist two firms belonging to different components that have an incentive to form an agreement between themselves. □

Proof of Proposition 2. If g^c is pairwise stable, then

$$(1-\gamma)\,\pi(1) \geq 2\pi(2) \tag{9}$$

By rewriting the last condition, we get $\gamma \leq \hat{\gamma}=1-\frac{2\pi(2)}{\pi(1)}$. If $\gamma \leq \hat{\gamma}=1-\frac{2\pi(2)}{\pi(1)}$, then $(1-\gamma)\,\pi(1) \geq 2\pi(2)$. Therefore, g^c is pairwise stable. □

Proof of Proposition 3. Assume that $n \geq 3$. If g^e is pair-wise stable then

$$(1-\gamma)^2\left[\pi(n-1)+(n-2)\,\pi(n)\right]<\pi(n)+\pi(n)+(n-2)\,\pi(n) \tag{10}$$

and, by straightforward calculations

$$\gamma>1-\left[\frac{n\pi(n)}{\left[\pi(n-1)+(n-2)\,\pi(n)\right]}\right]^{\frac{1}{2}}=\bar{\gamma}(n)$$

If $\gamma>\bar{\gamma}(n)$, then (10) holds. Therefore, g^e is pair-wise stable. *square*

Proof of Proposition 4. For simplicity, we assume just two complete components g_1 and g_2. For each firm $i \in g_1$, n_1 is the number of active firms in its market, and for each firm $j \in g_2$, n_2 is the number of active firms in its market. Let us define $\gamma(n_i):=\frac{\pi(n_i-1)-2\pi(n_i)}{\pi(n_i-1)+\sum_{k\neq j,gi=0}\pi(n_k)}$.

We are interested in knowing whether $\gamma\left(n_1\right)>\gamma\left(n_2\right)$. That is,

$$\frac{\pi\left(n_1-1\right)-2\pi\left(n_1\right)}{\pi\left(n_1-1\right)+\left(n-n_2+1\right)\pi\left(n_2\right)}>\frac{\pi\left(n_2-1\right)-2\pi\left(n_2\right)}{\pi\left(n_2-1\right)+\left(n-n_1+1\right)\pi\left(n_1\right)}$$

By solving the last expression, we get that $A > B$ where

$$A := (n - n_1 + 1)\,\pi(n_1)\,\pi(n_1 - 1) - 2\pi(n_1)\,\pi(n_2 - 1) - 2(n - n_1 + 1)\,[\pi(n_1)]^2 \tag{11}$$

and

$$B := (n - n_2 + 1)\,\pi(n_2)\,\pi(n_2 - 1) - 2\pi(n_2)\,\pi(n_1 - 1) - 2(n - n_2 + 1)\,[\pi(n_2)]^2 \tag{12}$$

In order to decide the sense of the inequality, we rearrange the above expression into the following two parts:

$$(n - n_1 + 1)\,\pi(n_1)\,[\pi(n_1 - 1) - 2\pi(n_1)] \geq (n - n_2 + 1)\,\pi(n_2)\,[\pi(n_2 - 1) - 2\pi(n_2)]$$

$$\pi(n_1)\,\pi(n_2 - 1) \leq \pi(n_2)\,\pi(n_1 - 1)$$

If $n_1 > n_2$, then (i) $(n - n_1 + 1) < (N - n_2 + 1)$; (ii) since individual profits are decreasing in n, $\pi(n_1) < \pi(n_2)$; (iii) since individual profits are log-convex in n, $[\pi(n_1 - 1) - 2\pi(n_1)] < [\pi(n_2 - 1) - 2\pi(n_2)]$. Therefore:

$$(n - n_1 + 1)\,\pi(n_1)\,[\pi(n_1 - 1) - 2\pi(n_1)] < (n - n_2 + 1)\,\pi(n_2)\,[\pi(n_2 - 1) - 2\pi(n_2)] \tag{13}$$

Additionally, if $n_1 > n_2$, then, by the log-convexity assumption, $\frac{\pi(n_2-1)}{\pi(n_2)} > \frac{\pi(n_1-1)}{\pi(n_1)}$. Hence

$$\pi(n_1)\,\pi(n_2 - 1) > \pi(n_2)\,\pi(n_1 - 1) \tag{14}$$

Therefore, if, $n_1 > n_2$, by (13) and (14), then

$$\gamma(n_1) < \gamma(n_2)$$

and we are done. □

Proof of Lemma 2. Note that with respect to n_j:

$$\frac{\triangle Z_i}{\triangle n_j} = \frac{\triangle W_i}{\triangle n_j} - \frac{\triangle C_i}{\triangle n_j}. \tag{13}$$

Tedious algebraic manipulations lead to:

$$\frac{\triangle W_i}{\triangle n_j} = \big(\pi(n_j) - \pi(n_j + 1)\big) > 0 \tag{14}$$

by A1 of the profit function. Similarly:

$$\frac{\triangle C_i}{\triangle n_j} = -\big(1 - \gamma(n_i - 1)(\gamma(n_j - 1) - \gamma(n_j)\big) \prod_{k \neq i, a_{ik}=1} (1 - \gamma(n_k)) < 0 \tag{15}$$

hence $\dfrac{\triangle Z_i}{\triangle n_j} > 0$

Now with respect to n_k:

$$\frac{\triangle Z_i}{\triangle n_k} = \frac{\triangle W_i}{\triangle n_k} - \frac{\triangle C_i}{\triangle n_k} = -\frac{\triangle C_i}{\triangle n_k}. \tag{16}$$

since $\dfrac{\triangle W_i}{\triangle n_k} = 0$. Tedious algebraic manipulations lead to:

$$\frac{\triangle C_i}{\triangle n_k} = \big(\gamma(n_i - 1) - \gamma(n_i)\big) + (\gamma(n_j - 1)(1 - \gamma(n_i - 1) \prod_{k \neq i, a_{ik}=1} (\gamma(n_k) - \gamma(n_k + 1)) > 0 \tag{17}$$

by A3. Finally, we have:

$$\frac{\triangle Z_i}{\triangle n_i} = \frac{\triangle W_i}{\triangle n_i} - \frac{\triangle C_i}{\triangle n_i}. \tag{18}$$

Tedious algebraic manipulations lead to:

$$\frac{\triangle W_i}{\triangle n_i} = \big(\pi(n_i - 1) - \pi(n_i)\big) + \big(\pi(n_i) - \pi(n_i + 1)\big) \leq 0 \tag{19}$$

by A2. Similarly:

$$\frac{\triangle C_i}{\triangle n_i} = (A + B) \prod_{k \neq i, a_{ik}=1} (1 - \gamma(n_k)) \tag{20}$$

where:

$$A := \big(\gamma(n_i) - \gamma(n_i + 1)\big) - \big(\gamma(n_i - 1) - \gamma(n_i)\big) \leq 0 \tag{21}$$

by A4. And since:

$$B := \gamma(n_j - 1)\big(\gamma(n_i - 1) - \gamma(n_i)\big) \geq 0 \tag{22}$$

by A3. Hence $A + B$ can be either positive or negative. □

Proof of Proposition 5. Assume network g is pair-wise stable. For all $m > \bar{m}^*$ and for all $m < \underline{m}* Z_i < 0$. Therefore, in a pair-wise stable network, no firm has more than $\bar{m}^*$ agreements and no less than $\underline{m}*$.

(a) Firstly, given a component of size $m\,(g_l)$, the number $m\,(g_l) - 1$ represents the maximal number of agreement that every firm in g_l may have. Recall that $\bar{m}^*$ is the maximal number of agreement such that $Z_i \geq 0$. Since components are symmetric, every firm in g_l has the same number of agreements. That is, for all pair of firms i and j that belong to g_l, then $m_i = m_j = m$. Assume now that i and j belong to g_l but $g_{ij} = 0$, if $m < m\,(g_l) - 1 \leq \bar{m}^*$, firms i and j will have incentives to form an agreement between them as $m < \bar{m}^*$. But it is a contradiction with the assumption of pair-wise stability of network g. Then, if $m\,(g_l) - 1 \leq \bar{m}^*$ all components must be complete and its member will have at most $\bar{m}^*$ agreements.

Second, let us assume that there exist two largest components such that their sizes are equal to $\bar{m}^* + 1$. As we have shown, these components must be complete and every firm inside them has $\bar{m}^*$ agreements. No firm inside these components has incentives to sever a link with a firm in the component as each firm in them has $\bar{m}^*$ agreements. Let us consider now a link between two firms belonging to each component. These firms have no incentives to sign one more agreements, as long as each one has $\bar{m}^*$ agreements, and this number is the largest number of links such that $Z_i \geq 0$.

Finally, let us consider a firm $i \in g_1$ and $j \in g_2$ such that $\bar{m}^* > m\,(g_1) > m\,(g_2)$. The firm j that belongs to the smaller component, refuses to sign an agreement with i, since $n_i < n_j$ and then, $\pi\,(n_j - 1) - \pi\,(n_i) < 0$. As $n - \bar{n} > 1$, isolated players have no incentives to form any agreements.

(b) Assume $m\,(g_l') = \max_{l=1,2,\ldots,p} \{m\,(g_l)\} > \bar{m}^* + 1$. Therefore, $m\,(g_l') - 1 > \bar{m}^*$. Since $\bar{m}^*$ is the maximal number of links such that $Z_i \geq 0$, every firm in g_l' has $\bar{m}^*$ agreements and then g_l' will not be fully interconnected. If each firm in g_l' has lesser agreements than $\bar{m}^*$, it will have incentives to form one more link. If a firm inside this component has more agreements than $\bar{m}^*$ and/or the component is fully interconnected, every firm inside g_l' will have incentives to sever a link, as long as $m(g_l') - 1 > \bar{m}^*$, and thus g would not be pair-wise stable.

Let us assume now that another component g_l'' such that $\bar{m}^* + 1 < m(g_l'') \leq m(g_l') \max_{l=1,2,\ldots,p}\{m(g_l)\}$. As before, g_l'' will not be fully interconnected and its members will have $\bar{m}^*$ links. No firm inside g_l'' has incentives to cut a link as it has $\bar{m}^*$ agreements. Moreover, no firm in g_l'' has incentives to sign another agreements since it has $\bar{m}^*$ links. Finally, let us consider that g_l'' is such that $m(g_l'') \leq \bar{m}^* + 1$. Then, it follows the proof in part (a). As $n - \bar{n} > 1$, the isolated players have no incentives to form any agreements. □

Proof of Proposition 6. Assume $g_{ij} = 1$. Then, $n_i = n_j = n$. Therefore, Z_i can be written as:

$$\pi(n) - 2\pi(n+1) - \left[\pi(n) - \pi(n+1) - \prod_{j\text{st}g_{ij}=1} (1-\gamma(n+1)) \left[(1-\gamma(n))^2 - (1-\gamma(n+1))\right]\right]$$

We must prove now that when $n = 1$, this expression is negative. That is, we must prove that:

$$-\pi(2) + (1-\gamma(2))^{n-2}\left[(\pi(1) - \pi(n))(1-\gamma(1))^2 - (\pi(2) - \pi(n))(1-\gamma(2))\right] < 0$$

For that, let us verify that the sign of bracket expression is also negative. First of all, let us observe that $\left[(1-\gamma(2)) - (1-\gamma(1))^2\right] > 0$. Therefore:

$$\pi(n)\left[(1-\gamma(2)) - (1-\gamma(1))^2\right] < \pi(2)\left[(1-\phi(2)) - (1-\gamma(1))^2\right] < \pi(2)(1-\gamma(2)) - \pi(1)(1-\gamma(1))^2$$

Consequently, $\underline{n}^*$ must be greater than 1 and the complete network will never be stable. When the industry is "sufficiently" large, the empty network emerge as a pair-wise stable network. □.

Proof of Proposition 7. Let $n - \overline{n}^* = \underline{m}^*$. We interpret $\underline{m}^*$ as the minimal number of agreement that a firm has to have in order to form an additional one. Therefore, when $n - \overline{n}^* = 1$ any two firm has incentive to form an additional agreement. However, if $n - \overline{n}^* > 1$ any two firms need to have more than one agreement in order to make profitable to form an additional link. □

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