

Strategic substitutability and complementarity in R&D networks

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Abstract

Firms form R&D joint ventures in order to benefit from the scale economies that make it likely to be successful in the R&D process. However, the same firms also compete in the market and R&D investments can lead to softer or more intense competition against specific rivals. We show, in a model of R&D networks with asymmetric spillovers that strategic substitutability and complementarity arises depending on whether the firms are connected in the network or not. We also show that the investment in R&D is negatively correlated to the degree of the R&D network. However, the presence of spillovers from neighbor and nonneighboring firms leads to higher R&D investment than in the absence of spillovers from non-connected firms.

Keywords: Supermodular games, R&D

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1 Introduction

Substantial attention has been devoted in the literature to the R&D activities of firms and their implications on competition. Since early, it has been recognized that research joint ventures may be necessary to attain the amounts of investment needed for the R&D projects to be successful. Likewise, It has been recognized that R&D joint ventures have implications on the intensity of firm competition or even may facilitate collusion in certain markets. Seminal papers include [3], [8], [12] and [10] and more recently [2]. Recently, the literature has focused on the study of R&D networks, taking in consideration that firms may cooperate with several partners at the same time, who do not cooperate among themselves. The network of collaboration plays, hence, an important role in the competitiveness of firms and on the impact of R&D on welfare. A seminal paper on R&D networks is [7]. They analyze the investment decision of firms in regular networks, i.e. when all firms have the same number of R&D partners. Also, in their work, the R&D cost reduction spillovers are symmetric between neighboring and non-neighboring firms, i. e. between firms that are linked in a research venture and firms that are not linked in a research venture. In this paper we extend their analysis to assess the strategic relationships that arise between firms who form R&D partnerships envisaging to reduce costs. R&D investments produce spillovers to the firms who participate in the partnership. We assume that firms outside of the partnership also receive spillovers, however, the intensity of the spillovers is lower. The spillovers are translated into marginal cost reduction and the R&D cost-reducing technology is linear in R&D investment as in [3]. We analyze a two stage game in which firms make their R&D investment decisions first and then compete in the product market. For the product market competition, we study both Cournot and price competition with differentiated product. Our paper is distinct from previous work in two ways. First, we study more general spillovers arising from the R&D network structures and second our focus is on the potential strategic complementarities or substitutabilities that arise in R&D investment. Regarding complementarities and substitutabilities we follow the definition of [4]. The strategies of the firms

of investing in R&D are strategic substitutes or complements depending on whether a more aggressive action by one firm lower or raises the rival's marginal returns of their own strategy. In [4] and likewise in [6], firms can use the investment in R&D to soften or intensify competition depending on the strategic interaction in the product market. In this paper, we show that different network structures lead to strategic complementarities or substitutabilities and hence may soften or intensify competition. To the best of our knowledge, this paper is the first to connect the network structure of research joint ventures and characterization of the strategic complementarities/substitutabilities between neighboring and non-neighboring firms.

2 Model and Results

We consider a model where firms are organized in a network. These firms play a two-stage game. In the first stage, each firm chooses a level of investment in R&D. The R&D investments and the network of R&D collaboration, define the costs of the firms. In the second stage the firms compete in the market, taking as given the costs of production. We are interested in characterizing the optimal investment levels depending on the strategic complementarities or substitutabilities that emerge from the network. Also, we study both price competition with differentiated product and quantity competition in the product market stage. We now develop the notation.

Network Let $N = \{1, 2, \dots, n\}$, $n > 3$ be the set of firms. For any two firms, i and j , we define g_{ij} as the network relationship established. g_{ij} is zero if there is no link between the firms and it is one if a link is established. g denotes the collection of all pairwise relationships established by the n firms. $g - g_{ij}$ denotes the network obtained by severing an existing link between firms i and j from network g , while $g + g_{ij}$ is the network obtained by adding a new link between firms i and j in network g . The set $N_i(g)$ denotes the set of firms with which firm i has a collaboration link in network

g . $\eta_i(g)$ be the cardinality of the set $N_i(g)$. We consider regular networks, in which all firms have the same number of links. In this case, k denotes the degree of the network, i.e. the number of links of each firm.¹ Firms form links unilaterally and link formation is costless.

R&D investment and spillovers Firms choose the R&D investment level unilaterally.

The investment of firm i is denoted e_i . The investment in R&D decreases the marginal cost of the firms represented by c . There is a spillover in the form of cost reduction to other firms in the market. This spillover is given by $\beta \in [0, 1]$ for firms linked to the firm who initiates the investment and it is given by $\delta \in [0, 1]$ for the firms that have no link to the firm who initiates the investment.² We assume that $\beta > \delta$. Formally, given a network g the investment and spillovers have the following impact on the marginal cost:

$$c_i = \bar{c} - e_i - \beta \sum_{l \in N_i(g)} e_l - \delta \sum_{m \notin N_i(g)} e_m$$

We assume that there is an upper bound on the investment of firms such that $c_i > 0$.³ Also, R&D investment is costly and the cost is given by $Z(e_i) = \gamma e_i^2$, so that there are decreasing returns to investment.

Product Market We analyze two different specifications to the product market competition. In the first specification the firms produce an homogeneous product and compete in quantities. In this case, the inverse demand function is $P = a - Q$, where $Q = \sum_{i \in N} q_i$. In the second specification, firms produce differentiated, although to some extent substitutable products and compete in prices. In this case, the demand function for a generic firm i is given by $q_i = a - p_i + b \sum_{r \neq i} p_r$, where $b = \frac{z}{n-1}$, for $z \in [0, 1]$.

¹When there are n firms, where n is an even number, $k^{max} = n - 1$ and at least one (in case of multiple, nonisomorphic) not necessarily connected regular graph exists for all $k \in \{1, 2, \dots, n - 1\}$.

²Although the general model of [7] assumes the possibility of asymmetric spillovers, the model is developed under the assumption that the spillover from the investment of nonconnected firms is zero.

³Namely we impose $e_i \in \left[0, \frac{\bar{c}}{(1+\beta k + \delta(n-k-1))}\right]$.

Subgame perfect equilibrium We obtain the subgame perfect equilibrium of the game by backward induction. We obtain the equilibrium profit of the product market competition stage as a function of the R&D investment levels of firms. Firms choose the optimal R&D investment.

2.1 Quantity competing firms

In this section we analyze the optimal investment level of the firms. We assume that firms compete in quantities in the product market and that the networks constituted in the first stage of the game are regular.

Given a network g , the firm i maximizes the payoffs given by

$$\pi_i(g) = \left(a - q_i - \sum_{j \neq i} q_j - c_i(g) \right) q_i - \gamma e_i(g)^2$$

The first order condition of the problem is

$$a - 2q_i - \sum_{j \neq i} q_j - c_i(g) = 0$$

Given that the costs are firm specific and depend on the R&D investments, we have in the product market equilibrium

$$q_i = \frac{a - nc_i(g) + \sum_{j \neq i} c_j}{n + 1}$$

The profits are

$$\pi_i(g) = \left(\frac{a - nc_i(g) + \sum_{j \neq i} c_j}{n + 1} \right)^2 - \gamma e_i(g)^2.$$

Denoting $A = a - nc_i(g) + \sum_{j \neq i} c_j$. We can rewrite the profit as

$$\pi_i(g) = \left(\frac{A}{n + 1} \right)^2 - \gamma e_i(g)^2$$

We have the following cost structure:

$$\begin{aligned}
c_i &= \bar{c} - e_i - \beta \sum_{l \in N_i(g)} e_l - \delta \sum_{m \notin N_i(g)} e_m \\
c_l &= \bar{c} - e_l - \beta \sum_{j \in N_l(g)} e_j - \delta \sum_{m \notin N_l(g)} e_m \\
c_m &= \bar{c} - e_m - \beta \sum_{j \in N_m(g)} e_j - \delta \sum_{m \notin N_m(g)} e_m
\end{aligned}$$

Given the regularity of the network,

$$\begin{aligned}
A &= a - c + (n - (n - k - 1)\delta - k\beta) e_i \\
&\quad ((n - k + 1)\beta - (n - k - 1)\delta - 1) k e_l \\
&\quad ((k + 2)\delta - k\beta - 1) (n - k - 1) e_m \\
\pi_i(g) &= \left(\frac{A}{n + 1} \right)^2 - \gamma e_i(g)^2
\end{aligned}$$

Proposition 1 *The investments in R&D of neighboring firms are strategic complements if*

$\frac{(n-k+1)\beta-1}{(n-k-1)} > \delta$ and substitutes otherwise.

Proof. Given the smoothness of the profit on the investment level e_i and e_l , strategic complementarity is equivalent to supermodularity of the profit function in (e_i, e_l) . Supermodularity

can be verified if $\frac{d^2 \pi_i}{de_i de_l} > 0$.

$$\frac{d\pi_i}{de_i} = 2 \frac{A}{(n+1)^2} \frac{dA}{de_i} - 2\gamma e_i$$

$$\begin{aligned}
\frac{d\pi_i^2}{de_i de_l} &= 2 \frac{1}{(n+1)^2} \left(\frac{dA}{de_l} \frac{dA}{de_i} + \frac{dA^2}{de_i de_l} A \right) \\
&= 2 \frac{1}{(n+1)^2} \left(\frac{dA}{de_l} \frac{dA}{de_i} \right) \\
&= 2 \frac{k}{(n+1)^2} ((n - k + 1)\beta - (n - k - 1)\delta - 1) (n - (n - k - 1)\delta - k\beta)
\end{aligned}$$

We have that $(n - (n - k - 1)\delta - k\beta)$ is always positive for $\beta > \delta$. The condition for supermodularity is then obtained if

$$\begin{aligned} ((n - k + 1)\beta - (n - k - 1)\delta - 1) &> 0 \iff \\ \delta &< \frac{(n - k + 1)\beta - 1}{(n - k - 1)}. \end{aligned}$$

■

Notice that if the network is complete, i.e. $k = n - 1$, then, strategic complementarity with the neighbors investment arises for high β , namely for $\beta > \frac{1}{2}$, otherwise they are strategic substitutes.

Also, as long as $k < n - 2$ and $\beta > \frac{1}{2}$, then an increase in the degree of the R&D network corresponds to a less stringent restriction for strategic complementarity with the R&D investment of the neighbors.⁴

Proposition 2 *The investments in R&D of non-neighboring firms are strategic complements if $\delta > \frac{(k\beta+1)}{(k+2)}$, and substitutes otherwise.*

Proof. Given the smoothness of the profit on the investment level e_i and e_m , strategic complementarity is equivalent to supermodularity of the profit function in (e_i, e_m) . Supermodularity can be verified if $\frac{d^2\pi_i}{de_i de_m} > 0$.

$$\frac{d\pi_i}{de_i} = 2 \frac{A}{(n+1)^2} \frac{dA}{de_i} - 2\gamma e_i$$

⁴We compare the condition under degree k and degree $k + 1$. We obtain two conditions: under k , $\frac{(n-k+1)\beta-1}{(n-k-1)} > \delta$. Under $k+1$, $\frac{(n-k-1+1)\beta-1}{(n-k-1-1)} > \delta$. If $k < n - 2$ and $\beta > \frac{1}{2}$, the second condition is larger than the first so, easier to attain.

$$\begin{aligned}
\frac{d\pi_i^2}{de_i de_m} &= 2 \frac{1}{(n+1)^2} \left(\frac{dA}{de_m} \frac{dA}{de_i} + \frac{dA^2}{de_i de_m} A \right) \\
&= 2 \frac{1}{(n+1)^2} \left(\frac{dA}{de_m} \frac{dA}{de_i} \right) \\
&= 2 \frac{k}{n+1} [(((k+2)\delta - k\beta - 1)(n-k-1))(n - (n-k-1)\delta - k\beta)]_{\beta=\tau, \delta=\tau}
\end{aligned}$$

We have that $(n - (n-k-1)\delta - k\beta)$ is always positive for $\beta > \delta$. The condition for supermodularity is then obtained if

$$\begin{aligned}
(((k+2)\delta - k\beta - 1)(n-k-1)) &> 0 \iff \\
\delta &> \frac{(k\beta + 1)}{(k+2)}.
\end{aligned}$$

■

In case of symmetric spillovers, strategic complementarities in investment levels occur for a high enough level of spillovers, otherwise, we have strategic substitutability.⁵

We will now provide some intuition on Proposition 1 and 2. For $k < n-1$ there are three regions of parameters that correspond to different strategic interaction. Namely:

- *Region I*: $\frac{(k\beta+1)}{(k+2)} < \delta < \frac{(n-k+1)\beta-1}{(n-k-1)}$, all investment is strategic complement.
- *Region II*: $\delta < \frac{(k\beta+1)}{(k+2)}$ and $\delta < \frac{(n-k+1)\beta-1}{(n-k-1)}$, investment is strategic complement with the neighbors and strategic substitute with the non-neighbors.
- *Region III*: $\frac{(n-k+1)\beta-1}{(n-k-1)} < \delta < \frac{(k\beta+1)}{(k+2)}$, all investment is strategic substitute.

Figure 1 depicts the regions of spillovers and the corresponding strategic substitutability and complementarity relations.

⁵ $\tau > \frac{1}{2}$.

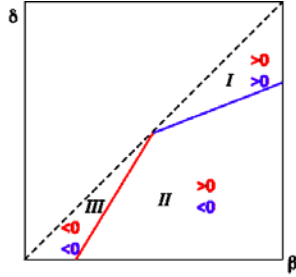


Figure 1: Regions of spillovers that originate different strategic interaction.

For some intuition of the results let's take *Region III*, where δ and β are small. Suppose a neighbor of i increases the investment in R&D, e_l . The marginal cost of firm l decreases. The marginal costs of every other firm, including i , decrease by very little due to the reduced spillovers. The reaction functions of the second stage behave as depicted in Figure 2.

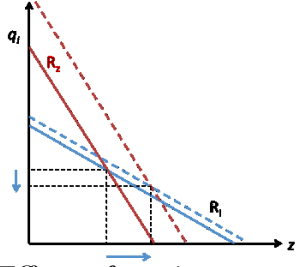


Figure 2: Effect of an increase in R&D investment by a neighboring firm for low δ and β .

Letting $z = \sum_{j \neq i} q_j$, we can see, the equilibrium production of firm i declines and the total equilibrium production of the remaining firms increases. As such, the return from investing in R&D for firm i is lower. The same is true, however even more intense, if we have a non-neighboring firm increasing the R&D investment. As β increases, it is more likely that the expansion of the reaction of firm i in the second stage increases, leading to higher production and hence stronger incentives to invest in R&D, so the investments become strategic complements, rather than substitutes.

Proposition 3 *An increase in the degree of interconnection, k , increases full the strategic substitutability area and decreases the full strategic complementarity area. Also, If $\beta > \frac{\delta+1}{3}$ and $\delta < \frac{(n-2)\beta-1}{n}$, the degree of the network has no effect on the strategic substitutability or complementarity of the investment in $R\&D$.*

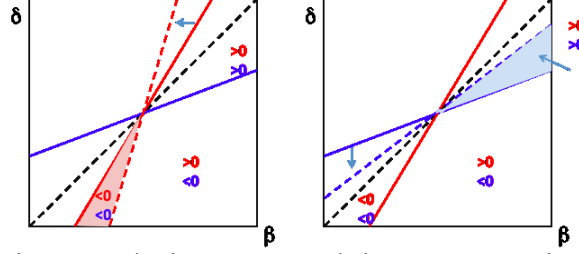


Figure 3: Effect of an increase in interconnectivity on strategic complementarities and substitutabilities.

Proposition 4 *Assuming that $\gamma > \left(\frac{(n-(n-k-1)\delta-k\beta)}{n+1}\right)^2$. The optimal level of investment is given by*

$$e^* = \frac{(a-c)(n-\delta(n-k-1)-k\beta)}{(\gamma(n+1)^2 - (n-\delta(n-k-1)-k\beta)(k\beta+\delta(n-k-1)+1))}.$$

Proof. Under the assumption that $\gamma > \left(\frac{(n-(n-k-1)\delta-k\beta)}{n+1}\right)^2$, the profit function is concave in e .⁶ So, the first order condition is necessary and sufficient for profit maximization. The first order condition is given by

$$\frac{d\pi_i}{de_i} = 0 \iff 2\frac{A}{(n+1)^2}\frac{dA}{de_i} - 2\gamma e_i = 0^7$$

⁶ $\frac{d^2\pi_i}{de_i^2} = 2\left(\frac{1}{(n+1)^2}\left(\left(\frac{dA}{de_i}\right)^2 + A\frac{d^2A}{de_i^2}\right) - \gamma\right) < 0 \iff \left(\frac{(n-(n-k-1)\delta-k\beta)}{n+1}\right)^2 < \gamma$
⁷ $\frac{d\pi_i}{de_i} = 2\frac{(a-c+(n-(n-k-1)\delta-k\beta)e_i+((n-k+1)\beta-(n-k-1)\delta-1)ke_i+((k+2)\delta-k\beta-1)(n-k-1)e_m)}{(n+1)^2} (n-(n-k-1)\delta-k\beta)-2\gamma e_i = 0 = 0$

In equilibrium $e_i = e_l = e_m = e$,

$$2 \frac{(a - c + (1 - \delta + k\beta + (n - k)\delta)e)}{(n + 1)^2} (n - (n - k - 1)\delta - k\beta) - 2\gamma e = 0$$

Solving for e , we obtain:

$$e^* = \frac{(a - c)(n - (n - k - 1)\delta - k\beta)}{(\gamma(n + 1)^2 - (1 - \delta + k\beta + (n - k)\delta)(n - (n - k - 1)\delta - k\beta))}$$

■

Notice that when $\beta = 1$ and $\delta = 0$, we obtain the same results as [7]. Also, if the spillovers are symmetric across neighbors and non-neighbors, for instance, if $\beta = \delta = \tau$, we have

$$e^* = \frac{(a - c)(n - \tau(n - 1))}{\gamma(n + 1)^2 + (n - (n - 1)\tau)(1 - (n - 1)\tau)}.$$

Proposition 5 *Partial and asymmetric spillovers between neighbors and non-neighbors lead to lower equilibrium investment in R&D.*

Proof. We must compare the R&D investment levels under asymmetric R&D spillovers and under absence of spillover from non-neighbors. Namely

$$\begin{aligned} e^*(\beta, \delta) &= \frac{(a - c)(n - (n - k - 1)\delta - k\beta)}{(\gamma(n + 1)^2 - (1 - \delta + k\beta + (n - k)\delta)(n - (n - k - 1)\delta - k\beta))} \\ e^*(1, 0) &= \frac{(a - c)(n - k)}{(\gamma(n + 1)^2 - (1 + k)(n - k))} \end{aligned}$$

This comparison leads to

$$e^*(\beta, \delta) < e^*(1, 0).$$

■

Finally, The investment in R&D is decreasing in the symmetric spillover, which is in alignment with conventional models of R&D joint ventures. We obtain as well that the level

of investment decreases with interconnectivity, however, its sensitivity is lower than in the absence of non-neighbor spillovers (as in [7])

$$e^*(k+1) - e^*(k) < 0.$$

2.2 Price competition with differentiated product

Let $\mathcal{N}$ be the set of all firms in the market. The set $\mathcal{N}$ has cardinality n . The firms are distinguished by their marginal cost of production: There is product differentiation and firms compete in prices. The demand function of a generic firm h is given by:

$$q_h = a - p_h + b \sum_{r \neq h} p_r$$

We assume that $b = \frac{1}{n-1}$, for simplicity. Each firm chooses prices to maximize profits. Namely:

$$\max_{p_h} \pi_h = \left(a - p_h + b \sum_{r \neq h} p_r \right) (p_h - c_h)$$

The first order condition for profit maximization is:⁸

$$\begin{aligned} \frac{\partial \pi_h}{\partial p_h} &= 0 \iff \left(a - p_h + b \sum_{r \neq h} p_r \right) - (p_h - c_h) = 0 \\ &\iff a - 2p_h + b \sum_{r \neq h} p_r + c_h = 0 \iff \\ &\iff a - (2+b)p_h + b \sum_{r \in \mathcal{N}} p_r + c_h = 0 \end{aligned}$$

Summing over $h \in \mathcal{N}$,

$$na - (2+b) \sum_{r \in \mathcal{N}} p_r + bn \sum_{r \in \mathcal{N}} p_r + \sum_{r \in \mathcal{N}} c_r = 0$$

⁸The second order condition is verified.

$$na - (2 + b - bn) \sum_{r \in \mathcal{N}} p_r + \sum_{h \in \mathcal{N}} c_h = 0$$

$$\sum_{r \in \mathcal{N}} p_r = \frac{1}{(2 + b - bn)} \left(na + \sum_{h \in \mathcal{N}} c_h \right)$$

$$a - (2 + b) p_h + b \frac{1}{(2 - b(n - 1))} \left(na + \sum_{h \in \mathcal{N}} c_h \right) + c_h = 0$$

$$p_h = \frac{a + b \frac{1}{(2 - b(n - 1))} \left(na + \sum_{h \in \mathcal{N}} c_h \right) + c_h}{2 + b}$$

$$p_h = \frac{a + c_h}{2 + b} + \frac{b \left(na + \sum_{h \in \mathcal{N}} c_h \right)}{(2 + b)(2 - b(n - 1))}$$

$$p_h = \frac{a + c_h}{2 + b} + \frac{bc_h}{(2 + b)(2 + b - bN)} + \frac{b \left(na + \sum_{r \neq h} c_r \right)}{(2 + b)(2 + b - bn)}$$

$$p_h = \frac{a(2 + b - bn) + c_h(2 + 2b - bn)}{(2 + b)(2 + b - bn)} + \frac{b \left(na + \sum_{r \neq h} c_r \right)}{(2 + b)(2 + b - bn)}$$

So, the equilibrium profits of the price competition stage are:

$$\pi_h = \left(a - (1 + b) p_h + b \sum_h p_h \right) (p_h - c_h)$$

In equilibrium

$$p_h - c_h = \frac{a - (1 + b) c_h}{2 + b} + \frac{b \left(na + \sum_{h \in \mathcal{N}} c_h \right)}{(2 + b)(2 - b(n - 1))}$$

So,

$$\pi_h = \left(\frac{a - (1+b)c_h}{2+b} + \frac{b \left(na + \sum_{j \in N} c_j \right)}{(2+b)(2-b(n-1))} \right)^2$$

$$\pi_h = \frac{1}{(2+b)^2} \left(a - (1+b)c_h + \frac{b \left(na + \sum_{j \in N} c_j \right)}{(2-b(n-1))} \right)^2$$

We can separate with respect to c_h and let $(2-b(n-1)) = \Delta$

$$\pi_h = \left(\frac{b}{b+2} \right)^2 \frac{1}{\Delta^2 b^2} \left(a(b+2) + (b - (1+b)\Delta) c_h + b \sum_{r \neq h} c_r \right)^2$$

Notice that $\sum_{r \neq h} c_r = \sum_{l \in N_h} c_l + \sum_{m \notin N_h} c_m$

Due to symmetry, all neighbors of h will have the same cost (c_l) and the rest of the agents will have same cost c_m .

Also, It is assumed that my non-neighbors are not connected to my neighbors. (Which is true for the well accepted Erdos-Renyi networks (or a network with low clustering).

Hence,

$$\begin{aligned} \sum_{r \neq h} c_r &= \sum_{l \in N_h} c_l + \sum_{m \notin N_h} c_m = k(c_l) + (n-k-1)c_m \\ &= k \left(c - e_l - \beta \sum_{j \in N_l} e_j - \delta \sum_{s \notin N_l} e_s \right) + (n-k-1) \left(c - e_m - \beta \sum_{j \in N_m} e_j - \delta \sum_{t \notin N_m} e_t \right) \end{aligned}$$

We can rewrite the profits as

$$\pi_h = \left(\frac{b}{b+2} \right)^2 \frac{1}{\Delta^2 b^2} (a(b+2) + \phi(e_h, e_l, e_m))^2 - \gamma e_h^2.^9$$

We can now the strategic complementarities and substitutabilities that arise in this case.

Consider first the effect of own investment in the profit, namely

$$\frac{d\pi_h}{de_h} = \left(\frac{b}{b+2} \right)^2 \frac{1}{\Delta^2 b^2} 2(a(b+2) + \phi(e_h, e_l, e_m)) + \frac{d\phi}{de_h} - 2\gamma e_h$$

Proposition 6 *The investments in R&D of neighboring firms are strategic complements if $\frac{(n-2)\beta-1}{(n-k-1)} < \delta$ and substitutes otherwise.*

Proof. The profits are smooth in e_h and e_l . As such, supermodularity of the payoffs is

obtained for $\frac{d^2\pi_h}{de_h de_l} > 0$.

$$\begin{aligned} \frac{d^2\pi_h}{de_h de_l} &= \left(\frac{b}{b+2} \right)^2 \frac{1}{b^2} 2 \frac{d\phi}{de_l} > 0 \\ &= \left(\frac{1}{b+2} \right)^2 2k(-\beta + b(\beta + (n-k-1)\delta + 1)) > 0 \end{aligned}$$

Given that $b = \frac{1}{n-1}$,

$$\frac{(n-2)\beta-1}{(n-k-1)} < \delta$$

■

Proposition 7 *The investments in R&D of non-neighboring firms are strategic complements if $\frac{k\beta+(k+1)}{(n-1)} > \delta$ and substitutes otherwise.*

⁹Where $\phi(e_h, e_l, e_m) = ((n-1)b+w)c - (w+b(k\beta+(n-k-1)\delta))e_h - (kw\beta+b(k\beta+(n-k-1)k\delta+k))e_l - ((n-k-1)w\delta+b((n-k-1)k\beta+k(n-k-1)+n-k-1))e_m$, and we define $w = (b-(1+b)\Delta)$.

Proof. The profits are smooth in e_h and e_l . As such, supermodularity of the payoffs is obtained for $\frac{d^2\pi_h}{de_h de_m} > 0$.

$$\begin{aligned}
\frac{d^2\pi_h}{de_h de_m} &= \left(\frac{b}{b+2}\right)^2 \frac{2}{b^2} \frac{d\phi}{de_m} \\
&= 2(k + \delta + k\beta - n\delta + 1)(n-1) \frac{n-k-1}{(2n-1)^2} > 0 \iff \\
&\quad (k + \delta + k\beta - n\delta + 1) > 0 \iff \\
\frac{k + k\beta + 1}{(n-1)} &> \delta.
\end{aligned}$$

■

3 Conclusion

In this paper, we reveal that firms use R&D connections differently, depending on the nature of the strategic relationship with their neighbors and with their non-neighbors. We show that if there is asymmetry in the spillovers between connected firms and non-connected firms then different strategic interaction arises. Namely, the R&D investments may be strategic substitutes or strategic complements. We study an extension of [7] in which firms compete in quantities and connected firms provide a higher spillover than unconnected firms. However, unconnected firm's R&D investment still produce some spillovers. We obtain that the investment in R&D is decreasing with the degree of the network and that strategic substitutabilities/complementarities arise according to the relationship between the spillovers from differently connected firms. Namely, for low spillovers, we obtain strategic complementarities. However, if the spillovers of the non-neighboring firms are higher, then, an increase in their R&D levels, induces higher competition from non-collaborators which induces the firm to increase the R&D level. This result unveils a perverse effect of interconnectivity. Firms may create a joint venture to enjoy the scale economies that are needed for the R&D projects to be viable, however, a complete cut-out of the non-connected firms may lead to further

reduction of the investment in R&D. In our model, even weak spillovers from non-connected firms produce incentives for R&D investment to be higher, hence reducing the prices. The outcome is similar both in quantity and in price competition.

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