Networks of knowledge among unionized firms

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Abstract. We develop a model of strategic networks in order to analyze how trade unions will affect the stability of R&D networks through which knowledge is transmitted in an oligopolistic industry. Whenever firms settle wages, the partially connected network is likely to emerge in the long run if and only if knowledge spillovers are large enough. However, when unions settle wages, the complete network is the unique stable network. In other words, the stronger the union bargaining power is, the more symmetric stable R&D networks will be. In terms of network efficiency, the partially connected network (when firms settle wages) does not Pareto dominate the complete network (when unions settle wages) and vice versa. JEL classification: C70, L13, L20, J50, D85

Réseaux de connaissance entre des firmes syndiquées. Nous développons un modèle de réseaux stratégiques afin d'analyser comment les syndicats vont affecter la stabilité des réseaux R&D par lesquels les connaissances sont transmises dans une industrie oligopolistique. Lorsque les firmes fixent les salaires, le réseau partiellement connecté émerge à long-terme si et seulement si les externalités de connaissance sont très grandes. Cependant, lorsque les syndicats fixent les salaires, le réseau complet est l'unique réseau stable. En d'autres mots, plus les syndicats sont puissants, plus les réseaux de R&D stables sont symétriques. En ce qui concerne l'efficacité des réseaux, le réseau partiellement connecté (lorsque les firmes fixent les salaires) ne domine pas au sens de Pareto le réseau complet (lorsque les syndicats fixent les salaires) et vice versa.

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1. Introduction

The purpose of this paper is to study how institutional features such as unionization will affect the strategic incentives to form bilateral R&D collaborations in oligopolistic industries. Many markets are characterized by inter-firm collaboration in R&D activity. The collection of bilateral R&D collaborations between the firms defines a R&D network.[1] Biotechnology was one of the industries with the largest number of strategic technology alliances all around the world during the period 1980–2000. Hagedoorn (2002) has reported that in 2000 there were 199 strategic alliances in the biotechnology industry out of 575 strategic alliances counted overall, making biotechnology the first industry in the ranking followed by the information technology (184 alliances) and automotive (53 alliances). Biotechnology is a very relevant industry for Canada, which is one of the top five countries in this vital field. The Canadian biotechnology industry has grown rapidly since 1988 and there were 490 biotechnology innovative firms in Canada in 2003.[2]

Table 1 provides some information about alliances in the Canadian biotechnology industry for the year 2001: the total number of firms in each province, the percentage of firms with alliances, the number of firms having between 1 and 5 alliances (category A), the number of firms having between 6 and 10 alliances (category B), and the number of firms having more than 11 alliances (category C). We observe that about 30% of firms in Ontario, Quebec, British Columbia, and Alberta do have alliances. Since the precise data about the number of alliances for each firm in order to compute the mean and variance for such alliances are not available, we have opted for calculating an approximation of these statistics by assigning an arbitrary number of links for firms in each category. In particular, for categories A, B, and C we have assigned 3, 8, and 15 alliances, respectively. We then observe that Quebec has the smallest variance, or the most symmetric R&D network, whereas Alberta has the largest variance, that is, the most asymmetric R&D network. These observations are confirmed by table 2, where we report the total number of alliances for some cities, the firm with more alliances in each city, and its number of alliances. In Alberta, the major players, Biomira and Synsorb, were part of more than half the total number of alliances in Edmonton and Calgary, respectively, whereas in Quebec, one of the major players, Aeterna, was part of less than a third of the total number of alliances in Quebec City.

1 Powell, Koput and Smith-Doerr (1996) have reported evidence that innovation takes place more and more within the network in which the firm is embedded. Inter-firm linkages help firms to develop and absorb technology.

2 More than half are in the Human Health sector (53%) and 70% are located in Quebec, Ontario, and British Columbia. Biotechnology innovative firms generated $3.8 billion in 2003 in biotechnology revenues. Biotechnology R&D expenses tripled between 1997 and 2003, going from $494 million to $1.5 billion. In 2003 biotechnology firms employed 75,448 employees, of which 11,863 (16%) had biotechnology-related responsibilities (see Raoub, Salonious, and McNiven 2004).

TABLE 1
Alliances in the Canadian biotechnology industry for the year 2001

Province	No. firms	% with alliances	No. firms in Each category A	B	C	Mean	Variance
Ontario	101	29	28	4	8	1.60	10.94
Quebec	130	34.5	33	7	5	1.67	9.35
British Columbia	69	30	11	7	3	1.88	12.16
Alberta	24	29.5	4	0	3	2.15	18.26

SOURCE: SECOR, *Canadian Alliances in Biotechnology*, 2001

TABLE 2
Major players in Canadian biotechnology industry alliances for the year 2001

City	Total no. of alliances	Major player	Major player's no. of alliances
Edmonton (Alberta)	51	Biomira	29
Québec City (Québec)	26	Aeterna	8
Belleville (Ontario)	20	Bioniche	20
Calgary (Alberta)	14	Synsorb	11
Ottawa (Ontario)	10	Adherex	4
Kingston (Ontario)	8	Molecular Mining	5
Victoria (B.C.)	8	StressGen	8

SOURCE: SECOR, *Canadian Alliances in Biotechnology*, 2003

Most alliances or collaborative agreements involve firms located in unionized countries. The collective bargaining coverage, the bargaining system, and the union bargaining power differ among countries. The union bargaining power cannot be observed. However, the union density and the strike activity are very good proxies of it (see Vannetelbosch 1996). The union bargaining power derives from the union's ability to present the firm with a credible and sustainable threat of strike action. Union power is therefore increasing in the union's ability to convert the threat into action, which depends on trade union membership. Table 3 reports unionization rates (densities) in 2005 for the manufacturing industry and for all industrial sectors (membership and coverage) in Canada. Quebec is the most unionized province and Alberta the least unionized. Table 3 also reports statistics about disputes that occurred from 2003 to 2005.[3] Quebec, the province with the highest union density, posted the largest share of strikes and lockouts (336, or 45%), followed by Ontario (230, or 31%). Alberta, the province with the lowest union density, had by far the smallest share of strikes and lockouts (8, or

3 Approximately 84% of the 743 work stoppages and 87% of the 9.1 million resulting workdays lost were initiated by unions, the rest by employers. More than a quarter (29%) of the strikes and lockouts took place in manufacturing.

TABLE 3
Unionization rates by province for the manufacturing industry and for all industries (2005) and strikes and lockouts and person-days not worked by province (2003–2005), Canada

	2005 Unionization rates			2003–2005			
				Strikes		Days not worked	
Province	Manufact.	Members	Coverage	#	%	# (× 1000)	%
Ontario	26.4	27.0	28.0	230	31.0	1385	15.3
Quebec	36.1	36.9	40.7	336	45.2	2684	29.6
Bristish Columbia	31.0	31.0	33.1	38	5.1	1007	11.1
Prairies:	24.8						
- Alberta	-	21.9	23.8	8	1.1	113	1.2
- Saskatchewan	-	33.6	35.1	19	2.6	104	1.1
- Manitoba	-	35.5	37.8	20	2.7	47	0.5

SOURCE: Statistics Canada, *Perspectives on Labour and Income* (August 2006)

1.1%). Union densities and strike data suggest that unions in Quebec had much more bargaining power or were much stronger than unions in Alberta. It therefore seems that Alberta, the least unionized province, has the most asymmetric R&D network, whereas Quebec, the most unionized province, has the most symmetric R&D network.

All these observations support the view that the union bargaining power may play a role in explaining the R&D network architecture, and that it is likely that the R&D network architecture in regions with strong unions will tend to be more symmetric than in regions with weak unions. These conclusions should be taken cautiously without having controlled for some other variables that might be important. Thus, future econometric research needs to confirm these conclusions through empirical tests of the relationship between unions and R&D networks.

The aim of this paper is to provide a theoretical study of how institutional features such as unionization will affect the formation of bilateral R&D collaborations and the effective R&D outputs in oligopolistic industries. In particular, we are interested in addressing the following questions.

i) What are the strategic incentives for competing firms seeking for process innovations to form bilateral collaborations where knowledge is transmitted; and, therefore, what is the network structure that will endogenously arise once the bilateral collaborations are established?
ii) How might network structure change if it is either the firm or the trade union that is deciding about wages?

To answer these questions we develop a four-stage game in a setting with three competing firms in a homogeneous good industry. In stage one, firms decide the bilateral R&D collaborations (or links) they are going to establish. The purpose of these collaboration links is both to increase the opportunities for inter-partner learning and to share R&D knowledge in order to create an in-house innovation. The collection of bilateral links between firms defines a network of knowledge transmission. There are four possible network architectures.[4] In the *complete network*, every pair of firms is linked and the pattern of R&D knowledge transmission is the broadest. In the *star network*, there is a 'hub' firm directly linked to every other firm, while none of the other 'spoke' firms has a direct link with any other, although they are indirectly connected. In the *partially connected network*, two firms are linked, while the third one is isolated. In the *empty network*, there are no collaboration links and there is no knowledge transmission. The strategic decision for each firm to form direct collaboration links is driven by two opposing effects. On the one hand, a collaborating firm shares part of its competitive advantage due to its own investment in R&D, but it benefits partially from its collaborators' investments in R&D, and from its indirect partnerships. On the other hand, an isolated firm conceals its research knowledge and fully internalizes the competitive advantage due to its R&D investments, but it does not get any benefit from others' R&D investments. In stage two, each firm chooses independently and simultaneously a level of R&D effort translating to a reduction in its marginal costs of production, which depends on both the specific network of research knowledge and the role of the firm within the network.[5] The collaboration links generate knowledge spillovers that will help each firm to further reduce marginal production costs. In stage three, wages are settled at the firm level.[6] For tractability, we consider two extreme cases of wage determination: (i) each firm chooses its own wage (or there is no union), which is our benchmark; (ii) each union chooses the wage, which is the monopoly-union model. In stage four, oligopolistic firms compete in quantities.

The literature on networks of collaboration in R&D industries was initiated by the influential paper by Goyal and Moraga-González (2001). They analyzed the incentives for R&D collaboration between non-unionized firms, possibly not competitors, and the network architecture that would endogenously arise.[7] R&D

4 Depending on the particular network structure, firms might be directly and/or indirectly connected. For instance, firms 1 and 2 may form a collaboration link, as may firms 2 and 3, while firms 1 and 3 do not. We say that firm 1 (2) and firm 2 (3) are directly connected, while firm 1 and firm 3 are indirectly connected.

5 Firms collaborate in R&D but do not cooperate on R&D effort choices. For a general background on R&D cooperation in oligopoly the reader is directed to Amir (2000), d'Aspremont and Jacquemin (1988), Kamien, Muller, and Zang (1992) and Katz (1986), among others.

6 In Canada wage bargaining mostly takes place at the plant- or firm-level. Among the OECD countries Canada has the most decentralized and the least coordinated wage negotiations (see Driffill 2006).

7 Goyal and Joshi (2003) have studied networks of collaboration between oligopolistic and non-unionized firms. In contrast to our model, a collaboration link between two firms involves a fixed cost and leads to an exogenously specified reduction in marginal production cost. Recently, Goyal, Konovalov, and Moraga-González (2005) have developed a model of R&D competition and collaboration in which each firm carries out both independent in-house research and joint research projects with other firms.

collaboration also consists of knowledge transmission and there is no cooperation on the R&D efforts. Goyal and Moraga-González analyzed the case of symmetric networks where every firm has the same number of collaboration links as well as the three-firm case. Our contribution to this literature is twofold. First, we examine the effect of unions on the formation of R&D networks. Second, we are interested in the transmission of both tacit and codified knowledge, thereby complementing Goyal and Moraga-González's work, which seems more appropriate for transmission of codified knowledge only. As a consequence, the way knowledge is transmitted in our model differs from that of Goyal and Moraga-González. First, the transmission of knowledge can be partially appropriated by partners, whereas in Goyal and Moraga-González the transmission of knowledge is always fully appropriated. Second, knowledge spillovers from indirect partnerships are smaller than those obtained from direct collaborations because knowledge spillovers deteriorate in the distance of the relationship. Third, there are no public knowledge spillovers, since we assume that no knowledge is transmitted to firms that are unconnected.[8] In Goyal and Moraga-González, no distinction is made between indirectly connected partners and unconnected firms, since both get the same public knowledge spillovers. Thus, our model strengthens the role of the R&D network.

We find that whenever firms settle wages, the complete network is always pairwise stable, while the partially connected network is stable if and only if knowledge spillovers are large enough. The complete network is not robust to coalitional deviations; meanwhile, the partially connected network remains stable even against coalitional deviations when knowledge spillovers are large enough. The intuition behind the stability of the partially connected network relies on the cost asymmetry between the linked firms and the isolated firm, which discourages a linked firm from forming an additional link when spillovers are large. Moreover, the isolated firm will tend to be pushed out of the market as spillovers become very large. Once spillovers, and consequently the cost asymmetry, are sufficiently small, the partially connected network becomes unstable.

However, when unions settle wages, a large share of the benefits of the linked firms goes to the unions, which diminishes their competitive advantage with respect to the isolated firm. As a consequence, collaborating firms have fewer incentives to do R&D; meanwhile, the isolated firm may even undertake more R&D effort in the presence of unions. In fact, unionization considerably reduces the cost asymmetry between the linked firms and the isolated firm. Thus, unionization destabilizes the partially connected network, making the complete network the unique pairwise stable network. We conclude that the stable network that will emerge in the long run is likely to be different, regardless of whether firms settle

8 Since tacit knowledge is more difficult to transmit than codified knowledge, it is not excluded that unconnected firms would benefit from spillovers when codified knowledge is the most relevant one. However, Saviotti (1998) has found evidence that the degree of public knowledge of a given piece of codified knowledge is proportional to its age and to the fraction of agents knowing the code.

wages or unions settle wages. In terms of network efficiency, the partially connected network (when firms settle wages) does not Pareto dominate the complete network (when unions settle wages) and vice versa.

The literature analyzing the relationship between the level of unionization and the incentives to undertake strategic R&D in oligopoly is scarce.[9] Tauman and Weiss (1987) were the first to propose a theoretical analysis of the relationship between firm-level unions' bargaining power and firms' strategic incentives to undertake R&D projects in a tournament R&D set-up. They have shown that the unionized duopolist has a greater incentive than the non-unionized one to adopt the new technology, which drives to lower labour requirements.[10] In this paper we consider a new way by which unions will affect the innovation process, that is, through their impact on the emerging network of R&D bilateral collaborations, and we show that the network architecture turns out to be a key element in understanding the incentives to invest in R&D in the presence of unions.

The paper is organized as follows. In section 2 we present the model. In section 3 we derive the equilibrium R&D outputs, wages, quantities produced, and profits for each possible network architecture. In section 4 we analyze the stability of R&D networks. In section 5 we conclude.

2. The model

We develop a four-stage game in a setting with three competing firms that produce some homogeneous good.[11] In the first stage, firms decide the bilateral R&D collaborations (or links) they are going to establish in order to maximize their respective profits. The collection of pairwise links between the firms defines a network of R&D collaborations. In a network, firms are the nodes and each link

9 Menezes-Filho and Van Reenen (2003) have reported that, neglecting strategic R&D, the effects of unions on innovation are generally ambiguous both in theory and in empirical practice. However, there is some emerging consensus of a negative association between unions and R&D in North America (see Acs and Audretsch 1988; Betts, Odgers, and Wilson 2001). No such relationship is found for Europe (see Schnabel and Wagner 1992; Menezes-Filho, Ulph, and Van Reenen 1998).

10 Ulph and Ulph (1994) have considered a Cournot duopoly in a race for a labour-saving process innovation, and they have found that strategic R&D could be increasing in the union bargaining strength when firms bargain with firm-level unions over employment and wages. Calabuig and González-Maestre (2002) have shown that, for a small market size, a labour-saving process innovation is more likely to be adopted by a firm in the presence of a centralized union compared with a decentralized one. Recently, Haucap and Wey (2004) have shown that, for two firms engaged in a patent race for a labour-saving process innovation, innovation incentives are not monotone in the degree of centralization of wage bargaining.

11 The timing of this four-stage game is intended to reflect the planning horizon usually associated with the respective decisions. Investment decisions are mostly long run, while wage contracts are usually negotiated for a much shorter time horizon, and product market quantities can usually be adjusted on an even shorter basis. For instance, PhRMA, which represents the leading research-based pharmaceutical and biotechnology companies in the United States, states that time horizons (for R&D investments) may be quite long in the pharmaceutical industry, where it takes 14 years on average to develop and introduce a new chemical entity (NCE) (see www.phrma.org).

indicates a bilateral R&D collaboration. Thus, a network g is simply a list of the pairs of firms that are linked to each other and $ij \in g$ indicates that i and j are linked under the network g. The network obtained by adding link ij to an existing network g is denoted $g + ij$, and the network obtained by deleting link ij from an existing network g is denoted $g - ij$. There are four possible network architectures: (i) the complete network, g^c, in which every pair of firms is linked, (ii) the star network, g^s, in which there is one firm that is linked to the other two firms, (iii) the partially connected network, g^p, in which two firms have a link and the third firm is isolated, and (iv) the empty network, g^e, in which there are no collaboration links. In the star network, the firm that is linked to the other two firms is called the 'hub' firm, while the other two firms are called the 'spoke' firms.

In the second stage, each firm undertakes R&D to look for cost-reducing innovations. The innovation technology is produced under decreasing returns to scale with the sole capital input k_i: $x_i = \sqrt{k_i}$, where x_i is firm i's research output (or effort). It follows that the cost function for technology is given by $\tilde{C}_i(r, x_i) = r \cdot (x_i)^2$, where r is the price of capital. The production technology is modelled as a Leontief function $q_i = \min\{L_i, 1/\theta_i \cdot K_i\}$, where q_i is output, L_i is labour, K_i is capital, and θ_i is the fixed proportion at which the two factors are combined.[12] This technology gives rise to the cost function for producing output q_i, $C_i(w_i, r, q_i) = (w_i + r\theta_i) \cdot q_i$, where w_i is the wage paid by firm i to its workers. The price of capital is normalized to one, $r = 1$. This assumption suffices to ensure non-negativity of all variables.[13] There is a function that relates the research output to the marginal cost of production. This function is a mapping from $(\{x_1, x_2, x_3\}, g)$ to θ_i,

$$\theta_i = \bar{c} - x_i - \phi\left(\frac{x_j}{t(ij)} + \frac{x_k}{t(ik)}\right), \quad i \neq j \neq k,$$

where $t(ij)$ is the number of links in the shortest path between i and j (setting $t(ij) = \infty$ if there is no path between i and j) and the parameter $\phi \in (0, 1]$ measures the spillovers obtained from R&D collaborations.[14] Spillovers from indirect collaborations are smaller than those obtained from direct R&D collaborations and

12 We assume that inputs are complements and the ratio capital-labour depends only on R&D efforts, not on relative prices of inputs. Our objective is to focus on the effect of unions on the structures of firms' collaborations, not on how the wage bargaining affects the relative input prices, and then the minimizing cost combination of inputs.

13 We assume that the price of capital used for R&D and the price of capital used for production are equal. We have analyzed a slightly more general model, where both prices may differ. The analysis of that model yields very similar results, as shown in the appendix. The additional price parameter makes the computation cumbersome, so we restrict our attention to the equal prices case in the main text.

14 This innovation process allows the firm to produce the same level of output with less capital. One of the most important innovations that reduced capital requirements was the introduction of the telegraph in the 19th century. Nowadays information technology (mobile phones, PCs, PDA, satellites) is a leading example of innovations that reduce the requirements of capital.

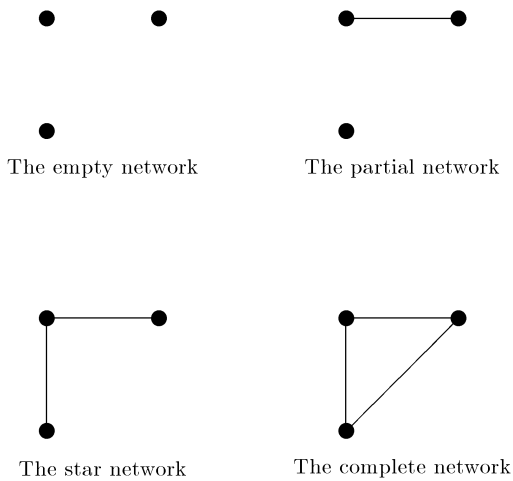

FIGURE 1 Four possible network architectures

deteriorate in the distance of the relationship. Given a network g and the collection of research outputs $\{x_1, x_2, x_3\}$, the marginal cost of production for firm i becomes

$$c_i(g) = w_i + \bar{c} - X_i \quad \text{with} \quad X_i \equiv x_i + \phi\left(\frac{x_j}{t(ij)} + \frac{x_k}{t(ik)}\right),$$

where X_i is the effective R&D output of firm i. That is, X_i is firm i's total cost reduction obtained from its own research, x_i, and from the research knowledge of firms connected with i, which is partially absorbed, depending on ϕ.

In the third stage, wages are settled at the firm level. The wages and the R&D outputs, along with the network of collaborations, define the costs of the firms. Associated with each firm there is a risk-neutral union. The workforce for each firm is drawn from separate pools of labour, and the union objective is to maximize the economic rent,

$$U_i(w_i, \bar{w}, L_i) = L_i \cdot (w_i - \bar{w}),$$

where $\bar{w}$ is the reservation wage.[15] Without loss of generality, the reservation wage is set equal to zero, $\bar{w} = 0$.[16] Two extreme cases are considered: (i) each

15 In general, the reservation wage $\bar{w}$ depends positively on the expected outside-industry wage, the unemployment benefit, and the turnover rate and negatively on the unemployment rate. We implicitly assume that pools of labour at each firm are large enough and/or mobility of workers is weak (for instance, firms may be located in different linguistic regions), so that for any given equilibrium wage differentials among firms, firms are not constrained in labour force. It follows that the reservation wage $\bar{w}$ is greater than the competitive wage w_c (the one that would equalize labour offer and demand), $\bar{w} \geq w_c$.

16 It can be shown that all results are qualitatively robust to this assumption.

firm simultaneously chooses the wage that maximizes profits, taking as given the wage chosen by the other firms; (ii) each union simultaneously chooses the wage that maximizes the economic rent, taking as given the wage chosen by the other unions.[17]

In the fourth stage, firms compete in quantities in the oligopolistic market, taking as given the costs of production. Let $P(Q) = a - Q$ be the market-clearing price when aggregate quantity on the market is $Q \equiv \sum_i q_i$. More precisely, $P(Q) = a - Q$ for $Q < a$, and $P(Q) = 0$ otherwise, with $a > 0$. Thus, firm i's profits in a collaboration network g are given by

$$\Pi_i(g) = \left[a - q_i(g) - \sum_{j \neq i} q_j(g) - c_i(g) \right] \cdot q_i(g) - [x_i(g)]^2 .$$

This four-stage game is solved backwards. We first look for subgame perfect equilibria of the multi-stage game made up of stage two to stage four. Then, stage one is solved using the concept of pairwise stability, which overcomes the multiplicity of (implausible) Nash equilibria in the network formation stage.

3. Equilibrium R&D outputs, wages and quantities

Before looking for stable R&D networks, one has to derive for each possible network architecture the equilibrium R&D outputs, wages, quantities produced, and profits.

3.1. Complete network

In the last stage of the game, the R&D collaboration links have already been chosen, the wage levels have already been determined, and the research efforts have already been chosen. Under Cournot competition the firms compete by simultaneously choosing their outputs to maximize profits with price adjusting to clear the market. The unique Nash equilibrium of the Cournot competition stage game is either

$$q_i(g^c, f) = \frac{1}{4}(a - \bar{c} + 3x_i - x_j - x_k + 2(x_j + x_k - x_i)\phi), \quad i \neq j \neq k,$$

17 By tractability, we do not consider a version of the right-to-manage model where unions and firms have bargaining power over wages. However, Mauleon and Vannetelbosch (2005, 2006) have shown that, if the union bargaining power is not too big, it is optimal for unions that maximize the rents to send to the negotiation table delegates who maximize the wage, and such negotiations may mimic the monopoly-union outcomes where the unions choose their most preferred wages. See also Jones (1989).

if the firm settles the wage, and

$$q_i(g^c, u) = \frac{1}{4}(a - \bar{c} - 3w_i + w_j + w_k + 3x_i - x_j - x_k + 2(x_j + x_k - x_i)\phi), \quad i \neq j \neq k.$$

if the union settles the wage. The symbol $f(u)$ indicates that the firm (union) chooses the wage. In the third stage, wages are settled at the firm level. We have $w_i(g^c, f) = 0$. Standard computations give us

$$w_i(g^c, u) = \frac{1}{28}(7(a - \bar{c}) + x_i(13 - 6\phi) - (x_j + x_k)(3 - 10\phi)), \quad i \neq j \neq k.$$

In the second stage, the firms simultaneously choose their research outputs to maximize profits, anticipating perfectly wages and outputs. The unique (symmetric) Nash equilibrium of this stage game is

$$x_i^*(g^c, f) = \frac{(3 - 2\phi)(a - \bar{c})}{13 - 4\phi(1 - \phi)}$$

$$x_i^*(g^c, u) = \frac{9(13 - 6\phi)(a - \bar{c})}{1675 - 36\phi(5 - 3\phi)}.$$

We observe that research efforts are decreasing with spillovers (ϕ). Then, one can easily obtain the subgame perfect Nash equilibrium outputs, profits, and wages:

$$q_i^*(g^c, f) = \frac{4(a - \bar{c})}{13 - 4\phi(1 - \phi)}$$

$$\Pi_i^*(g^c, f) = \frac{(7 + 4(3 - \phi)\phi)(a - \bar{c})^2}{(13 - 4\phi(1 - \phi))^2}$$

$$q_i^*(g^c, u) = \frac{336(a - \bar{c})}{1675 - 36\phi(5 - 3\phi)}$$

$$\Pi_i^*(g^c, u) = \frac{9(151 - 18\phi)(73 + 18\phi)(a - \bar{c})^2}{(1675 - 36\phi(5 - 3\phi))^2}$$

$$w_i^*(g^c, u) = \frac{448(a - \bar{c})}{1675 - 36\phi(5 - 3\phi)}.$$

3.2. Other networks

In the appendix we provide for the partially connected, star, and empty network, the equilibrium R&D outputs, wages, quantities produced, and profits.

In the presence of unions, any competitive advantage of a rival has to be shared with the union. Thus, the competitive advantage due to increasing research effort will be smaller with unions rather than without unions. For instance, a marginal increase of x_j will reduce j's marginal cost, but in the presence of unions, part of the marginal cost (wage) will increase with x_j, which partially compensates the reduction in the marginal cost of production. We could say that unions make research efforts less 'substitutes.' In the empty network g^e, R&D efforts are always strategic substitutes. In the complete network g^c, R&D efforts are strategic substitutes if spillovers are small and become strategic complements when spillovers are large. However, strategic interactions among R&D efforts of different firms become complex in the star network g^s. R&D efforts of the two 'spoke' firms are strategic substitutes when firms settle wages, regardless of what spillovers are. However, R&D efforts of the two 'spoke' firms become strategic complements when spillovers are large and unions settle wages. Finally, R&D efforts of the 'hub' firm and a 'spoke' firm are strategic substitutes for small spillovers but are strategic complements for large spillovers. In general, unionization increases the likelihood of R&D efforts being strategic complements.

PROPOSITION 1. *In the empty network g^e, the star network g^s, and the complete network g^c, at equilibrium, unions reduce research outputs, profits, and quantities, and unions increase wages and prices.*

All proofs can be found in the appendix. In the partial network g^p, R&D outputs of the collaborating firms can be either strategic substitutes or complements, depending on the spillovers parameter ϕ. However, the strategic interaction between R&D output of a collaborating firm and R&D output of the isolated one (or the opposite) is of substitution, regardless of spillovers size and unionization.

PROPOSITION 2. *In the partial network, g^p, at equilibrium, unions reduce research outputs, profits, and quantities of collaborating firms; unions reduce research outputs of the non-collaborating firm if and only if spillovers are weak* ($\phi < 0.547$); *unions reduce profits of the non-collaborating firm if and only if spillovers are weak* ($\phi < 0.633$)*; unions reduce quantities of the non-collaborating firm if and only if spillovers are very weak* ($\phi < 0.275$)*; and unions increase wages and prices.*

If unions choose wages, then individual R&D output of a firm is decreasing with the number of links the firm has and with the spillover parameter ϕ. If firms settle wages, then individual R&D output still decreases with the spillover parameter ϕ, except for the firms that collaborate in the partial network and for the 'hub' firm in the star network. Indeed, the research effort made by the 'hub' firm may increase or decrease with ϕ, depending on how large spillovers are. As ϕ goes from zero to one, research effort first increases with ϕ, then it starts to decrease with ϕ. But the relationship between individual R&D output and the number of links becomes much more complex. Nonetheless, aggregate R&D output is decreasing with the spillover parameter ϕ and with the

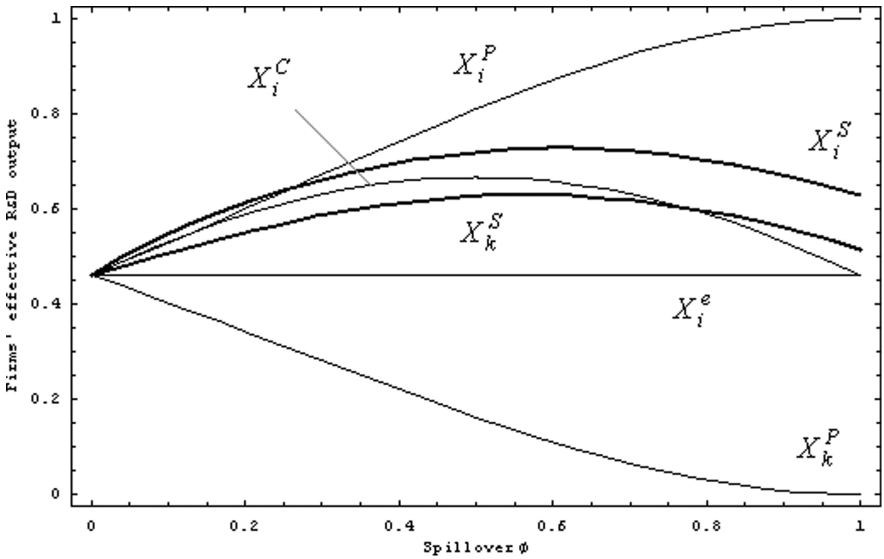

FIGURE 2 Firm's effective R&D when firms settle wages

number of collaborations, whatever the mode of wage settlement and the network architecture.

It is also interesting to analyze the evolution of effective R&D, since it is a measure of the reduction in marginal cost. In figure 2 and figure 3 we plot effective R&D outputs when firms settle wages and unions settle wages, respectively.[18] In all figures, (i) k denotes the isolated firm in the partially connected network g^p, while k denotes a 'spoke' firm in the star network g^s; (ii) i denotes a linked firm in the partially connected network g^p, while i denotes the 'hub' firm in the star network g^s; (iii) subscripts e, p, s, and c stand for empty, partially connected, star, and complete networks, respectively. We observe that, if unions settle wages, effective R&D output of any firm increases with the spillover parameter ϕ, except for very large spillovers and for the isolated firm in g^p. If firms settle wages, effective R&D output of any firm (except firms in g^p) first increases with ϕ, then decreases with ϕ, and reaches a maximum for values of ϕ close to $^1/_2$. Indeed, an increase in ϕ has, in general, a twofold effect on firm i's effective R&D. First, it increases firm i's benefits from the research knowledge of firms connected with i. Second, it reduces individual R&D outputs. Which one of the two effects dominates the other determines the relationship between effective R&D and ϕ.

18 All figures are plotted for $a = 4$ and $\bar{c} = 2$.

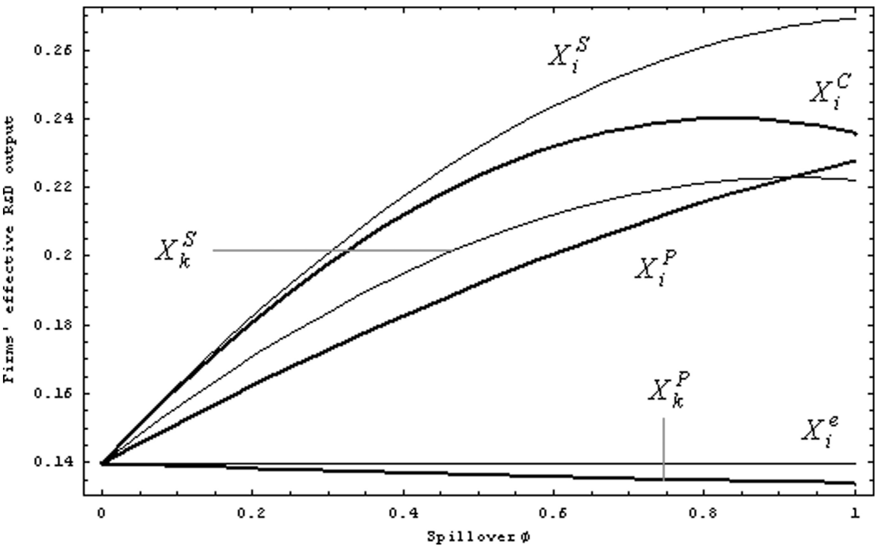

FIGURE 3 Firm's effective R&D when unions settle wages

4. Stable R&D networks

In the first stage, firms decide which bilateral R&D collaborations (or links) they are going to establish in order to maximize their respective profits, anticipating perfectly R&D outputs, wages, and quantities produced. A simple way to analyze the networks that one might expect to emerge in the long run is to examine a sort of equilibrium requirement that agents not benefit from altering the structure of the network. A weak version of such a condition is the pairwise stability notion defined by Jackson and Wolinsky (1996). A network is pairwise stable if no agent benefits from severing one of their links and no other two agents benefit from adding a link between them, with one benefiting strictly and the other at least weakly.

DEFINITION. *A network g is pairwise stable if*

i) for all $ij \in g$, $\Pi_i(g) \geq \Pi_i(g - ij)$ *and* $\Pi_j(g) \geq \Pi_j(g - ij)$, *and*
ii) for all $ij \notin g$, *if* $\Pi_i(g) < \Pi_i(g + ij)$ *then* $\Pi_j(g) > \Pi_j(g + ij)$.

This definition of stability is quite weak and should be seen as a necessary condition for strategic stability.

PROPOSITION 3. *Suppose firms settle wages. The complete network* g^c *is always pairwise stable. The partially connected network* g^p *is pairwise stable if and only if spillovers are large enough,* $\phi \geq \hat{\phi}$. *The star and empty networks (respectively,* g^s *and* g^e*) are never pairwise stable.*

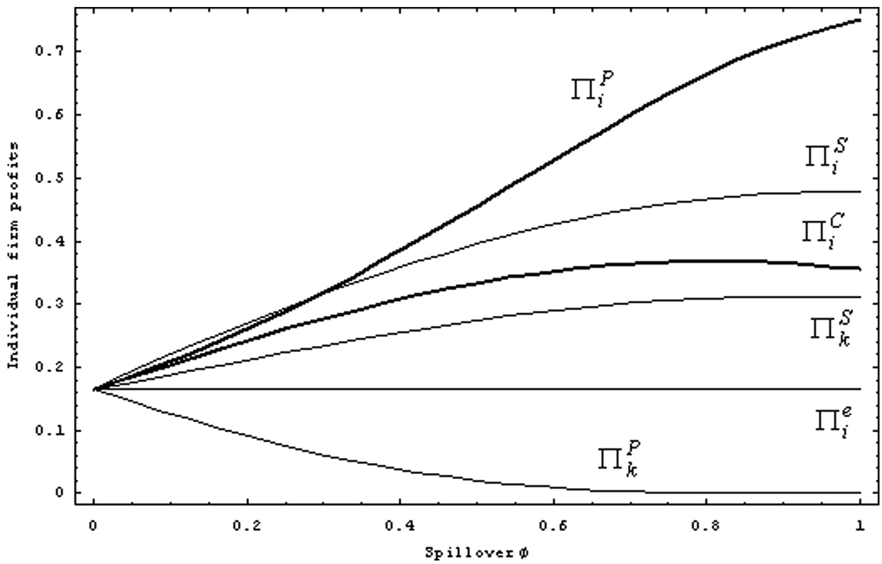

FIGURE 4 Individual firm profit when firms settle wages

In figure 4 we plot individual firm profits for each possible network architecture when firms settle wages.[19] The empty network g^e is never stable, because two firms have incentives to collaborate. Both firms are ex ante symmetric and, by collaborating, they will benefit from a cost advantage relative to the isolated firm. The star network g^s is never stable, because the 'spoke' firms that have only one link have incentives to link to each other. Both 'spoke' firms are ex ante symmetric and, by collaborating, they annihilate the cost advantage the 'hub' firm had relative to them. Thus, the complete network g^c is always pairwise stable. Whether the partially connected network g^p is stable will depend on spillovers ϕ. If spillovers are large enough, the isolated firm has a significant cost disadvantage, and it will tend to be pushed out of the market as spillovers become very large. Thus, collaborating firms may decide to keep isolated the third firm and to divide between them most of the market, letting only a small share go to the isolated firm, rather than forming a star network by offering a collaboration link to the isolated firm. On the contrary, if spillovers are small, collaborating firms have incentives to link with the isolated firm in order to become the 'hub' firm in the star network and to benefit from cost reductions due to the increase in effective R&D. The gains due to the increase in effective R&D are not offset by the increase in product competition. The former isolated firm is more competitive under the star network because it benefits directly from

19 In the Goyal and Moraga-González (2001) three-firm case, the partially connected network is pairwise stable only if public knowledge spillovers are very small. The complete network is always pairwise stable but never stable against coalitional deviations.

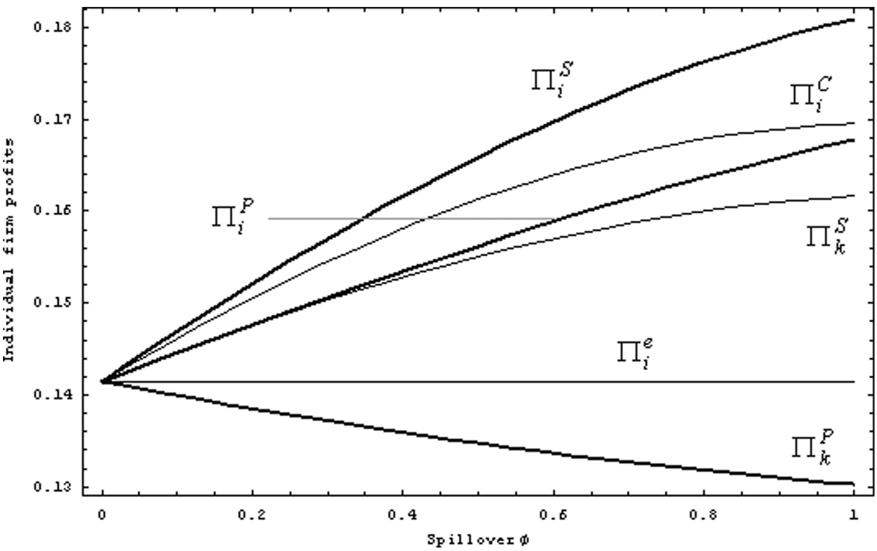

FIGURE 5 Individual firm profit when unions settle wages

spillovers from the 'hub' firm and indirectly from spillovers from the other 'spoke' firm.

As ϕ decreases, the profits of the firms in the different networks become similar, irrespective of the network structure (in the limiting case $\phi \to 0$ all the profits are equal). Thus, network structures become more important when spillovers are large.[20] Another observation concerns the impact of spillovers on the stability of different networks. Small spillovers destabilize the partially connected network rapidly. The intuition behind this is that the stability of the partially connected network relies on the great cost asymmetry existing between the linked firms and the isolated firm. It is this asymmetry that discourages a linked firm from forming a link with the isolated firm, for sufficiently large spillovers. As ϕ decreases, this asymmetry reduces, and that destabilizes the partially connected network g^p. Moreover, the larger ϕ is, the smaller the cost asymmetry existing between firms in the star network is, and the smaller cost advantage the 'hub' firm has. In contrast, the complete network remains stable for all values of ϕ, but losses from deleting a link diminish as ϕ decreases (in this sense the complete network becomes more vulnerable as ϕ decreases).

PROPOSITION 4. *Suppose unions settle wages. The complete network g^c is the unique pairwise stable network.*

In figure 5 we plot individual firm profits for each possible network architecture when unions settle wages. The empty network g^e still is never stable. Nor is the

20 Goyal and Moraga-González (2001) found that network structures are more important when public spillovers are modest. This is why we assume no public spillovers.

star network g^s ever stable. Indeed, 'spoke' firms that have only one link still have incentives to link to each other. Thus, the complete network g^c is pairwise stable. But once the unions settle wages, the partially connected network g^p is no longer stable, even when spillovers ϕ are large. Without unions, the isolated firm will tend to be pushed out of the market as spillovers become very large. However, under unionization, a large share of the benefits of the linked firms, thanks to cost reductions due to R&D collaborations, goes to the unions, which diminishes their competitive advantage with respect to the isolated firm. As a consequence, collaborating firms have fewer incentives to make R&D; meanwhile, the isolated firm may even make more R&D effort in the presence of unions. Even when ϕ goes to one, the isolated firm maintains a significant market share. In fact, unionization considerably reduces the asymmetry between the linked firms and the isolated firm. Thus, unionization destabilizes g^p, making g^c the unique pairwise stable network.[21]

4.1. Strong stability

While pairwise stability is natural and quite easy to work with, there are some limitations to the concept. For instance, pairwise stability considers only deviations by at most a pair of agents at a time. It might be that some group of agents could be made better off by some complicated reorganization of their links, which is not accounted for under pairwise stability.[22] Hence, Jackson and van den Nouweland (2005) have proposed the notion of strong stability. A strongly stable network is a network that is stable against changes in links by any coalition of agents. Since a strongly stable network is a pairwise stable network, the only two candidates to be strongly stable are g^p and g^c when firms settle wages. The complete network g^c is not strongly stable because two firms have incentives to form a coalition and to delete their links with the third firm, so moving to the partially connected network g^p. Such deviation was not allowed with pairwise stability. The partially connected network g^p remains stable when spillovers are large, $\phi \geq \hat{\phi}$. However, when unions settle wages, the complete network g^c is the unique strongly stable network. Thus, the stable network that will emerge in the long run is likely to be different, whether firms settle wages or unions settle wages.[23]

21 The stability results are robust to the case of an innovation that reduces the requirements of labour because unions would still reduce the cost asymmetries between firms having a different number of collaborations. Only salary levels would be affected.

22 Moreover, players cannot be farsighted in the sense that they do not forecast how others might react to their actions. Herings, Mauleon, and Vannetelbosch (2004) have proposed a general concept, social rationalizability, that predicts which coalitions or networks are going to emerge among farsighted players.

23 Firms and unions have very close aspirations in terms of network architecture. Suppose unions decide about links instead of firms. One can show that g^e, g^p, and g^s are never pairwise stable, and g^c is the unique pairwise stable network.

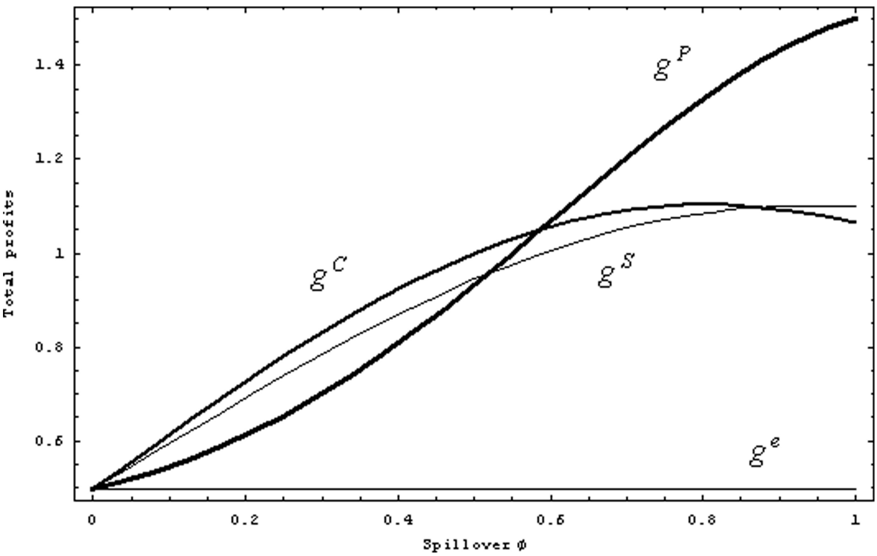

FIGURE 6 Aggregate industry profits when firms settle wages

4.2. Efficiency

A natural notion of efficiency is the notion of Pareto efficiency. A network g Pareto dominates g' if $\Pi_i(g) \geq \Pi_i(g')$ for all i with strict inequality for some i. A network g is Pareto efficient if it is not Pareto dominated by any other network. All networks are Pareto efficient, except the empty network, when firms settle wages. Once unions settle wages, only the complete and star networks remain Pareto efficient. In addition, the partially connected network (which is likely to emerge when firms settle wages) does not Pareto dominate the complete network (which is likely to emerge when unions settle wages) and vice versa.

Another notion of efficiency is simply the maximization of aggregate profits among all possible networks. A network g is (strongly) efficient if $\sum_i \Pi_i(g) \geq \sum_i \Pi_i(g')$ for any other network g'. In figure 6 and figure 7 we plot aggregate profits when firms settle wages and unions settle wages, respectively. Define ϕ_{TP} as the solution to equation $\sum_i \Pi_i(g^c, f) = \sum_i \Pi_i(g^p, f)$. We have that ϕ_{TP} exists and is unique and reveals that if $\phi < \phi_{TP}$, then g^c is the network that maximizes aggregate profits when firms settle wages; otherwise it is g^p. Notice that aggregate profits are not always increasing with the number of collaborations. We now provide some intuition for this pattern. When spillovers are large, the isolated firm tends to be pushed out of the market and the collaborating firms will obtain profits close to the duopoly case that are greater than those obtained in the complete network where all firms have equal market share. As $\phi \to 1$, we converge to a situation where in g^p two firms collaborate in R&D and share the whole market, while in g^c three firms collaborate in R&D and

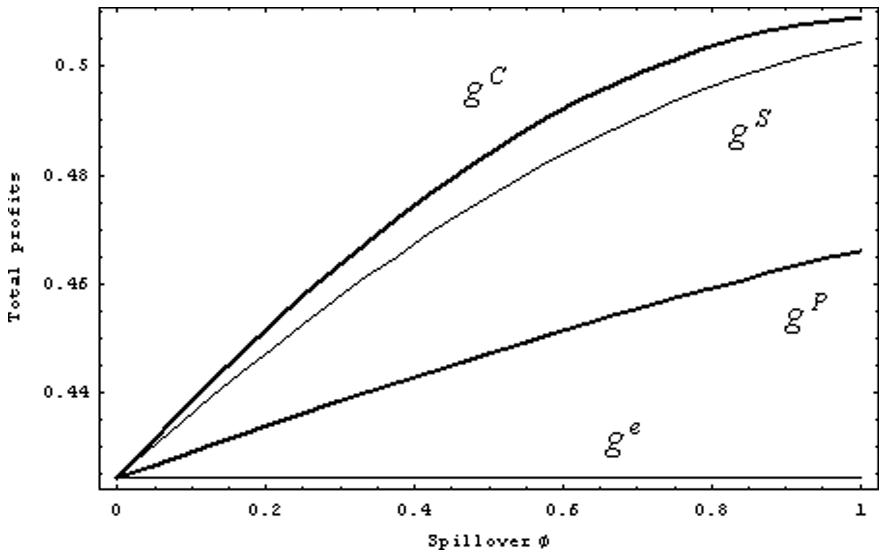

FIGURE 7 Aggregate industry profits when unions settle wages

share the whole market. However, we observe that the complete network g^c dominates in terms of aggregate profits when unions settle wages, and that aggregate profits are increasing with the number of collaborations and with the spillover parameter ϕ.

5. Conclusion

Up to now the role of trade unions in R&D has been limited to the study of whether unionization increases or decreases firms' incentives to undertake strategic R&D. This is a very restrictive approach, since the innovation process cannot be understood without considering that firms' conduct and performance are influenced in important ways by the strategic networks in which they are embedded. The primary objective of this paper has been to highlight a new way to see how unions affect the innovation process, that is, their role in the stability of networks formed to transmit tacit knowledge. By transmitting tacit knowledge, firms get knowledge spillovers, which make their R&D efforts more fruitful.

Within an oligopolistic industry made up of three competing firms that produce some homogeneous good, we have shown that, whenever firms settle wages, the partially connected network is likely to emerge in the long run if and only if knowledge spillovers are large enough. Indeed, the complete network is pairwise stable but not robust to coalitional deviations; meanwhile, the partially connected network is stable even against coalitional deviations when knowledge spillovers are large enough. However, when unions settle wages, the complete network is the unique stable network. In terms of network efficiency, the partially connected network (when firms settle wages) does not Pareto dominate the complete network (when unions settle wages) and vice versa.

5.1. More than three firms

Goyal and Moraga-González (2001) already mentioned that a complete analysis of stability for arbitrary n firms would be quite difficult, if not impossible (even for an analysis restricted to symmetric networks).[24] However, our analysis, restricted to three firms, allows us to draw some conjectures about what would happen if the industry had more than three firms. First, the empty network would never be pairwise stable, because two firms always have incentives to collaborate regardless of who settles wages. Second, the stronger the union bargaining power is, the more symmetric pairwise stable R&D networks would be. In fact strong unionization considerably reduces the asymmetry in costs between firms having a high number of links and firms having a low number of links, because unions are able to monopolize a large share of the benefits due to R&D collaborations through high wage demands. A challenge for future research would be to test empirically the relationship between the union bargaining power and the R&D network architecture.[25]

Appendix

We provide for the partially connected, star, and empty networks and the equilibrium R&D outputs, quantities produced, profits, and wages.

A.1. Partial network

Let k be the firm that is isolated and has no link. Firm i and firm j are linked to each other and share R&D activities. The unique subgame perfect Nash equilibrium of this multi-stage game leads to

$$x_i^*(g^p, f) = \frac{(3-\phi)(a-\bar{c})}{13-5(2-\phi)\phi}$$

$$x_k^*(g^p, f) = \frac{3(1-\phi)^2(a-\bar{c})}{13-5(2-\phi)\phi}$$

24 For symmetric networks, Goyal and Moraga-González (2001) have shown that individual R&D effort is declining in the level of collaborative activity, intermediate levels of collaborative activity are better for industry profits, and the complete network is always pairwise stable, while the empty network is never stable.

25 During the second half of the 1990s we have observed in the pharmaceutical biotechnology industry a particularly dense R&D network involving around 600 research partners where a small number of star players form the centre of research clusters. Despite this high level of network connection, we also observe 50 unique pairs of firms that collaborate only among themselves and thus are isolated from the R&D network and its knowledge flows. See Roijakkers and Hagedoorn (2006).

$$x_i^*(g^p, u) = \frac{6003(13 - 3\phi)(a - \bar{c})}{1117225 - 9027\phi(10 - 3\phi)}$$

$$x_k^*(g^p, u) = \frac{117(667 - 9\phi(10 - 3\phi))(a - \bar{c})}{1117225 - 9027\phi(10 - 3\phi)}.$$

We observe that research efforts are decreasing with spillovers (ϕ) when the union settles the wage. In case the firm settles the wage, research efforts made by the isolated firm k are always decreasing with ϕ, while research efforts made by firm i and firm j are decreasing with ϕ if and only if spillovers are strong enough. Subgame perfect Nash equilibrium outputs, profits, and wages are given by

$$q_i^*(g^p, f) = \frac{4(a - \bar{c})}{13 - 5(2 - \phi)\phi},$$

$$q_k^*(g^p, f) = \frac{4(1 - \phi)^2(a - \bar{c})}{13 - 5(2 - \phi)\phi}$$

$$q_i^*(g^p, u) = \frac{224112(a - \bar{c})}{1117225 - 9027\phi(10 - 3\phi)},$$

$$q_k^*(g^p, u) = \frac{336(667 - 9\phi(10 - 3\phi))(a - \bar{c})}{1117225 - 9027\phi(10 - 3\phi)}$$

$$\Pi_i^*(g^p, f) = \frac{(7 - \phi)(1 + \phi)(a - \bar{c})^2}{(13 - 5(2 - \phi)\phi)^2}$$

$$\Pi_k^*(g^p, f) = \frac{7(1 - \phi)^4(a - \bar{c})^2}{(13 - 5(2 - \phi)\phi)^2}$$

$$\Pi_i^*(g^p, u) = \frac{4004001(151 - 9\phi)(73 + 9\phi)(a - \bar{c})^2}{(1117225 - 9027\phi(10 - 3\phi))^2}$$

$$\Pi_k^*(g^p, u) = \frac{99207(667 - 9\phi(10 - 3\phi))^2(a - \bar{c})^2}{(1117225 - 9027\phi(10 - 3\phi))^2}$$

$$w_i^*(g^p, u) = \frac{298816(a - \bar{c})}{1117225 - 9027\phi(10 - 3\phi)}$$

$$w_k^*(g^p, u) = \frac{448(667 - 9\phi(10 - 3\phi))(a - \bar{c})}{1117225 - 9027\phi(10 - 3\phi)}.$$

A.2. Empty and star networks

In the case of the empty network, the unique (symmetric) subgame Nash equilibrium of this multi-stage game leads to

$$x_i^*(g^e, f) = \frac{3(a - \bar{c})}{13}, \quad x_i^*(g^e, u) = \frac{117(a - \bar{c})}{1675}$$

$$q_i^*(g^e, f) = \frac{4(a - \bar{c})}{13}, \quad q_i^*(g^e, u) = \frac{336(a - \bar{c})}{1675}$$

$$\Pi_i^*(g^e, f) = \frac{7(a-\bar{c})^2}{169}, \quad \Pi_i^*(g^e, u) = \frac{99207(a-\bar{c})^2}{1675^2}$$
$$w_i^*(g^e, f) = 0, \quad w_i^*(g^e, u) = \frac{448(a-\bar{c})}{1675}.$$

In the case of the star network, the unique (symmetric) subgame Nash equilibrium of this multi-stage game leads to (i is the 'hub' firm linked to the 'spoke' firms j and k)

$$x_i^*(g^s, f) = \frac{(3-2\phi)(4+3\phi(8-3\phi))(a-\bar{c})}{52+\phi(264-\phi(169-6\phi(15-4\phi)))}$$
$$x_j^*(g^s, f) = \frac{6(2-\phi)(1+\phi(5-2\phi))(a-\bar{c})}{52+\phi(264-\phi(169-6\phi(15-4\phi)))}$$

$$q_i^*(g^s, f) = \frac{4(4+3\phi(8-3\phi))(a-\bar{c})}{52+\phi(264-\phi(169-6\phi(15-4\phi)))}$$
$$q_j^*(g^s, f) = \frac{16(1+\phi(5-2\phi))(a-\bar{c})}{52+\phi(264-\phi(169-6\phi(15-4\phi)))}$$

$$\Pi_i^*(g^s, f) = \frac{(7-2\phi)(1+2\phi)(4+3(8-3\phi)\phi)^2(a-\bar{c})^2}{(52+\phi(264-\phi(169-6\phi(15-4\phi))))^2}$$
$$\Pi_j^*(g^s, f) = \frac{2(14-3\phi)(2+3\phi)(1+(5-2\phi)\phi)^2(a-\bar{c})^2}{(52+\phi(264-\phi(169-6\phi(15-4\phi))))^2},$$

when firms settle wages, and

$$x_i^*(g^s, u) = \frac{9(13-6\phi)(2668+27\phi(32-9\phi))(a-\bar{c})}{4468900+9\phi(94000-9\phi(3533-6\phi(191-36\phi)))}$$
$$x_j^*(g^s, u) = \frac{18(26-9\phi)(667+9\phi(19-6\phi))(a-\bar{c})}{4468900+9\phi(94000-9\phi(3533-6\phi(191-36\phi)))}$$
$$q_i^*(g^s, u) = \frac{336(2668+27\phi(32-9\phi))(a-\bar{c})}{4468900+9\phi(94000-9\phi(3533-6\phi(191-36\phi)))}$$
$$q_j^*(g^s, u) = \frac{1344(667+9\phi(19-6\phi))(a-\bar{c})}{4468900+9\phi(94000-9\phi(3533-6\phi(191-36\phi)))}$$
$$\Pi_i^*(g^s, u) = \frac{3(151-18\phi)(73+18\phi)(2668+27\phi(32-9\phi))^2(a-\bar{c})^2}{(4468900+9\phi(94000-9\phi(3533-6\phi(191-36\phi))))^2}$$
$$\Pi_j^*(g^s, u) = \frac{6(302-27\phi)(146+27\phi)(667+9\phi(19-6\phi))^2(a-\bar{c})^2}{(4468900+9\phi(94000-9\phi(3533-6\phi(191-36\phi))))^2}$$

$$w_i^*(g^s, u) = \frac{448(2668 + 27\phi(32 - 9\phi))(a - \bar{c})}{4468900 + 9\phi(94000 - 9\phi(3533 - 6\phi(191 - 36\phi)))}$$

$$w_j^*(g^s, u) = \frac{1792(667 + 9\phi(19 - 6\phi))(a - \bar{c})}{4468900 + 9\phi(94000 - 9\phi(3533 - 6\phi(191 - 36\phi)))},$$

when unions settle wages.

A.3. Proof of propositions 1 and 2

Comparing the subgame perfect Nash equilibrium R&D outputs, quantities produced, profits, and wages when firms settle wages with those when unions settle wages, we have (i) $x_i^*(g, f) \geq x_i^*(g, u)$, $\Pi_i^*(g, f) \geq \Pi_i^*(g, u)$, $q_i^*(g, f) \geq q_i^*(g, u)$, $w_i^*(g, f) \leq w_i^*(g, u)$, $P^*(g, f) \leq P^*(g, u)$ for $g \in \{g^e, g^s, g^c\}$ and $i \in \{1, 2, 3\}$; (ii) $x_i^*(g^p, f) \geq x_i^*(g^p, u)$, $\Pi_i^*(g^p, f) \geq \Pi_i^*(g^p, u)$, and $q_i^*(g^p, f) \geq q_i^*(g^p, u)$ for firm i linked in g^p; (iii) $x_k^*(g^p, f) \geq x_k^*(g^p, u)$ if and only if $\phi < 0.547$ for firm k isolated in g^p; (iv) $\Pi_k^*(g^p, f) \geq \Pi_k^*(g^p, u)$ if and only if $\phi < 0.633$ for firm k isolated in g^p; (v) $q_k^*(g^p, f) \geq q_k^*(g^p, u)$ if and only if $\phi < 0.275$ for firm k isolated in g^p; and (vi) $w_i^*(g^p, f) \leq w_i^*(g^p, u)$, $P^*(g^p, f) \leq P^*(g^p, u)$ for $i \in \{1, 2, 3\}$. ■

A.4. Proof of proposition 3

First we show that the complete network g^c is always pairwise stable. No pair of firms i and j have incentives to delete their link $ij \in g^c$. That is, $\Pi_i^*(g^c, f) > \Pi_i^*(g^s, f)$ and $\Pi_j^*(g^c, f) > \Pi_j^*(g^s, f)$ with $ij \notin g^s$. Since

$$\Pi_i^*(g^c, f) = \Pi_j^*(g^c, f) = \frac{(7 + 4(3 - \phi)\phi)(a - \bar{c})^2}{(13 - 4\phi(1 - \phi))^2} >$$

$$\Pi_i^*(g^s, f) = \Pi_j^*(g^s, f) = \frac{2(14 - 3\phi)(2 + 3\phi)(1 + (5 - 2\phi)\phi)^2(a - \bar{c})^2}{(52 + \phi(264 - \phi(169 - 6\phi(15 - 4\phi))))^2},$$

with $ij \notin g^s$, it follows that g^c is pairwise stable. Obviously, the star network g^s cannot be pairwise stable, since firms i and j have incentives to form the link $ij \notin g^s$.

Second, the empty network g^e is never pairwise stable. That is, $\Pi_i^*(g^p, f) > \Pi_i^*(g^e, f)$ and $\Pi_j^*(g^p, f) > \Pi_j^*(g^e, f)$, with $ij \in g^p$. Since

$$\Pi_i^*(g^p, f) = \frac{(7 - \phi)(1 + \phi)(a - \bar{c})^2}{(13 - 5\phi(2 - \phi))^2} >$$

$$\frac{7(a - \bar{c})^2}{(13)^2} = \Pi_i^*(g^e, f), \text{ with } i \in N(g^p),$$

it follows that g^e is not pairwise stable.

Third, the partially connected network g^p is pairwise stable if the spillovers are sufficiently large. Since the empty network is never pairwise stable, the network g^p is pairwise stable if and only if $\Pi_i^*(g^p, f) > \Pi_i^*(g^s, f)$ or $\Pi_j^*(g^p, f) > \Pi_j^*(g^s, f)$, with $ij \notin g^p$, $ij \in g^s$, and $j \notin N(g^p)$. Since

$$\Pi_j^*(g^p, f) = \frac{7(1-\phi)^4 (a-\bar{c})^2}{(13-5\phi(2-\phi))^2} <$$

$$\Pi_j^*(g^s, f) = \frac{2(14-3\phi)(2+3\phi)(1+(5-2\phi)\phi)^2(a-\bar{c})^2}{(52+\phi(264-\phi(169-6\phi(15-4\phi))))^2},$$

g^p is pairwise stable if and only if

$$\Pi_i^*(g^p, f) = \frac{(7-\phi)(1+\phi)(a-\bar{c})^2}{(13-5\phi(2-\phi))^2} >$$

$$\Pi_i^*(g^s, f) = \frac{(7-2\phi)(1+2\phi)(4+3(8-3\phi)\phi)^2(a-\bar{c})^2}{(52+\phi(264-\phi(169-6\phi(15-4\phi))))^2}.$$

Let $\hat{\phi}$ be a cutoff function that gives the value of ϕ such that $\Pi_i^*(g^p, f) = \Pi_i^*(g^s, f)$; $\hat{\phi} \simeq 0.285$. Then, g^p is pairwise stable if and only if $\phi \geq \hat{\phi}$. ■

A.5. Proof of proposition 4

First, we show that the complete network g^c is always pairwise stable. No pair of firms i and j have incentives to delete their link $ij \in g^c$. That is, $\Pi_i^*(g^c, u) > \Pi_i^*(g^s, u)$ and $\Pi_j^*(g^c, u) > \Pi_j^*(g^s, u)$, with $ij \notin g^s$. Since

$$\Pi_i^*(g^c, u) = \frac{9(151-18\phi)(73+18\phi)(a-\bar{c})^2}{(675-36\phi(5-3\phi))^2} >$$

$$\Pi_i^*(g^s, u) = \frac{6(302-27\phi)(146+27\phi)(667+9\phi(19-6\phi))^2(a-\bar{c})^2}{(4468900+9\phi(94000-9\phi(3533-6\phi(191-36\phi))))^2},$$

$$= \Pi_j^*(g^s, u)$$

with $ij \notin g^s$, it follows that g^c is pairwise stable. Obviously, the star network g^s cannot be pairwise stable, since firms i and j have incentives to form the link $ij \notin g^s$.

Second, the empty network g^e is never pairwise stable. That is, $\Pi_i^*(g^p, u) > \Pi_i^*(g^e, u)$ and $\Pi_j^*(g^p, u) > \Pi_j^*(g^e, u)$, with $ij \in g^p$. Since

$$\Pi_i^*(g^p, u) = \frac{4004001(151-9\phi)(73+9\phi)(a-\bar{c})^2}{(1117225-9027\phi(10-3\phi))^2} >$$

$$\frac{99207(a-\bar{c})^2}{2805625} = \Pi_i^*(g^e, u),$$

with $i \in N(g^p)$, it follows that g^e is not pairwise stable.

Third, the partially connected network g^p is never pairwise stable. That is, $\Pi_i^*(g^s, u) > \Pi_i^*(g^p, u)$ and $\Pi_j^*(g^s, u) > \Pi_j^*(g^p, u)$, with $ij \notin g^p$, $ij \in g^s$ and $i \notin N(g^p)$. Since we have

$$\Pi_i^*(g^s, u) = \frac{6(302 - 27\phi)(146 + 27\phi)(667 + 9\phi(19 - 6\phi))^2(a - \bar{c})^2}{(4468900 + 9\phi(94000 - 9\phi(3533 - 6\phi(191 - 36\phi))))^2} >$$

$$\Pi_i^*(g^p, u) = \frac{99207(667 - 9\phi(10 - 3\phi))^2(a - \bar{c})^2}{(1117225 - 9027\phi(10 - 3\phi))^2},$$

and

$$\Pi_j^*(g^p, u) = \frac{4004001(151 - 9\phi)(73 + 9\phi)(a - \bar{c})^2}{(1117225 - 9027\phi(10 - 3\phi))^2} <$$

$$\Pi_j^*(g^s, u) = \frac{3(151 - 18\phi)(73 + 18\phi)(2668 + 27\phi(32 - 9\phi))^2(a - \bar{c})^2}{(4468900 + 9\phi(94000 - 9\phi(3533 - 6\phi(191 - 36\phi))))^2},$$

with $ij \notin g^p$, $ij \in g^s$, $i \notin N(g^p)$, $j \in N(g^p)$, g^p is never pairwise stable. ■

A.6. Price of capital

Suppose that the price of capital used for R&D differs from the price of capital used for production. The cost function for technology becomes $\tilde{C}_i(\gamma, x_i) = \gamma \cdot (x_i)^2$, where γ is the price of capital used for R&D, while the cost function for producing output q_i still is given by $C_i(w_i, r, q_i) = (w_i + r\theta_i) \cdot q_i$, where r is the price of capital for production and is normalized to one, $r = 1$. We again look for stable R&D networks, after having derived for each possible network architecture the equilibrium R&D outputs, wages, quantities produced, and profits. Standard computations details are available from the authors upon request. A sufficient condition for ensuring non-negativity of all variables is

$$\gamma \geq \frac{1}{4}(3 - \phi)(1 + \phi) \quad \text{and} \quad \frac{3(3 + 2\phi - \phi^2)}{\phi(2 - 3\phi)} \geq \frac{a}{\bar{c}}.$$

The complete network g^c remains pairwise stable, regardless of who settles wages. The empty and star networks are never pairwise stable. The partially connected network g^p is pairwise stable only if firms settle wages and $\Pi_i^*(g^p, f) \geq \Pi_i^*(g^s, f)$, with $ij \in g^p$ and $ij, ik \in g^s$, where

$$\Pi_i^*(g^p, f) = \frac{\gamma(3 - 4\gamma)^2(16\gamma - (3 - \phi)^2)(a - \bar{c})^2}{(64\gamma^2 + 3(3 - \phi)(1 + \phi) - 4\gamma(15 + 2(2 - \phi)\phi))^2}$$

$$\Pi_i^*(g^s, f) = \frac{\gamma(16\gamma - (3 - 2\phi)^2)(16\gamma - 3(2 - \phi)(2 - 3\phi))^2(a - \bar{c})^2}{(256\gamma^2 - 3(2 - \phi)(3 - 2\phi)(2 + \phi(1 - 4\phi)) - 8\gamma(30 - \phi(36 - 11\phi)))^2}.$$

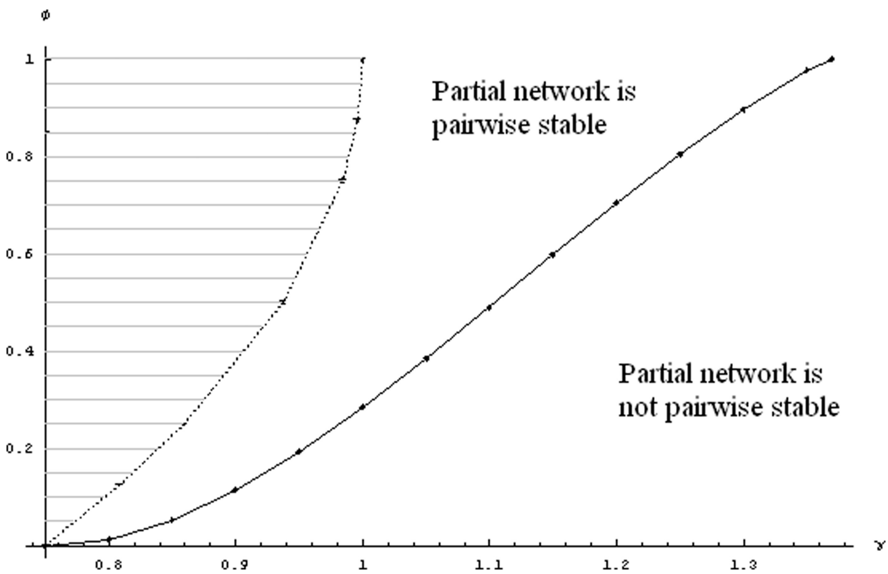

FIGURE A1 Stability of the partial network and the price of capital used for R&D.

Whether or not $\Pi_i^*(g^p, f) \geq \Pi_i^*(g^s, f)$ depends on ϕ and γ. In figure A1 we have plotted the range of parameters (ϕ and γ) for which the partially connected network is pairwise stable. The hatched area is the excluded area due to the above condition $\gamma \geq {}^1/_4\,(3-\phi)\,(1+\phi)$.

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