

R&D networks in an artificial industry

Lorenzo Zirulia

CESPRI-Bocconi University

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1. Introduction

Recently, technological strategic alliances have played an important role in the innovative activity of high tech industries. Some authors have talked about “the network as the locus of innovation” (Powell et alii, 1996).

While a large number of empirical studies has thrown light on this phenomenon, few formal models have been developed adopting a dynamic perspective.

I propose a simple simulative model capturing three aspects: technological complementarities as reason to form collaborative links among firms; absorptive capacity and relational capability as factors affecting the outcomes of collaborations. Section 2 proposes some stylized facts about strategic alliances and networks, while section 3 reviews previous formal models from different approaches. Section 4 describes the model, whose features and a comparison with existing models are the subject of section 5. Section 6 concludes.

2 Empirical evidence and appreciative theories on technological strategic alliances and networks

In this section I summarize some stylized facts about interfirm technological cooperation, and their common interpretations as proposed by appreciative theories put forth by economists, business scholars and sociologists. In particular, I will concentrate on the empirical facts and appreciative theories that are captured in some form by my formal model.

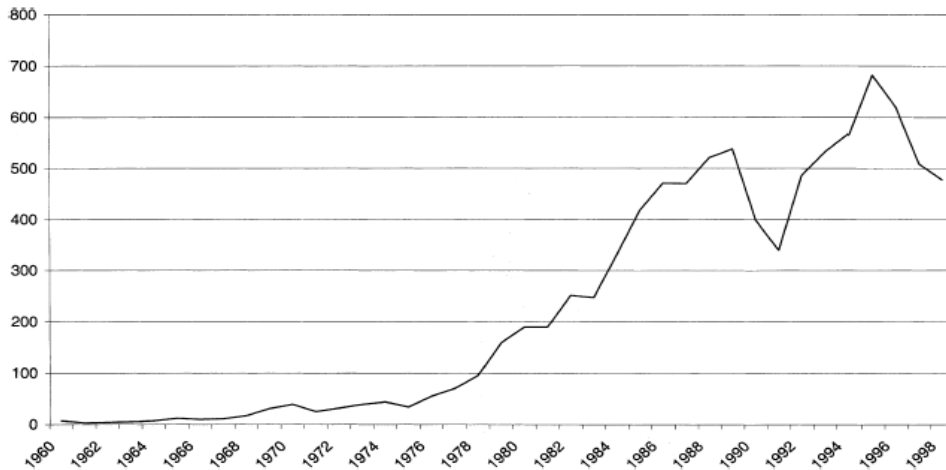
In this section, my aim is:

- i) to give the motivation of my work, by showing the relevance of technological cooperation, especially in high-tech industries;
- ii) to stress the main reasons for firms to enter into technological collaborations with other firms, as shown by empirical works;
- iii) to discuss the factors that affect the outcome of collaborations at firms' level, in particular the degree of knowledge transfer between collaborators;
- iv) to introduce the network perspective in the discussion of technological strategic alliances, both from a static and a dynamic view point.

2.1 Motivation: are technological collaborations a relevant phenomenon?

Figure 1, taken by Hagedoorn (2002), shows that, starting from the end of 70's, the number of yearly established technological agreements among firms have rapidly increased¹.

Figure 1- New established R&D partnership (1960-1998) Source: Hagedoorn (2002)



¹ Data are extracted by the MERIT-CATI databank, which collect information about more than 10.000 interfirm technological agreements over the world and across sectors. Examples of technological agreements considered by the data base are given by R&D joint ventures, joint development agreements, licensing and cross-licensing, and R&D contracts.

Figure 2 and 3, taken from the same source, show that technological agreements are particularly relevant in high tech industries, especially from the mid 80's. At the end the 90's, for instance, technological agreements in IT constitute more than 50% of all yearly established agreements, while agreements in pharmaceuticals constitute about 30%.

Figure 2: new R&D partnerships, for low, medium, high tech industries (percentages). Source: Hagedoorn (2002).

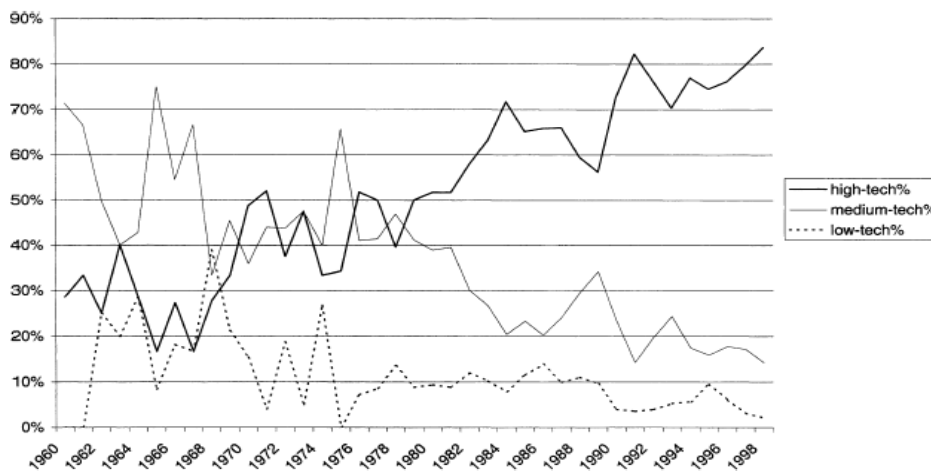
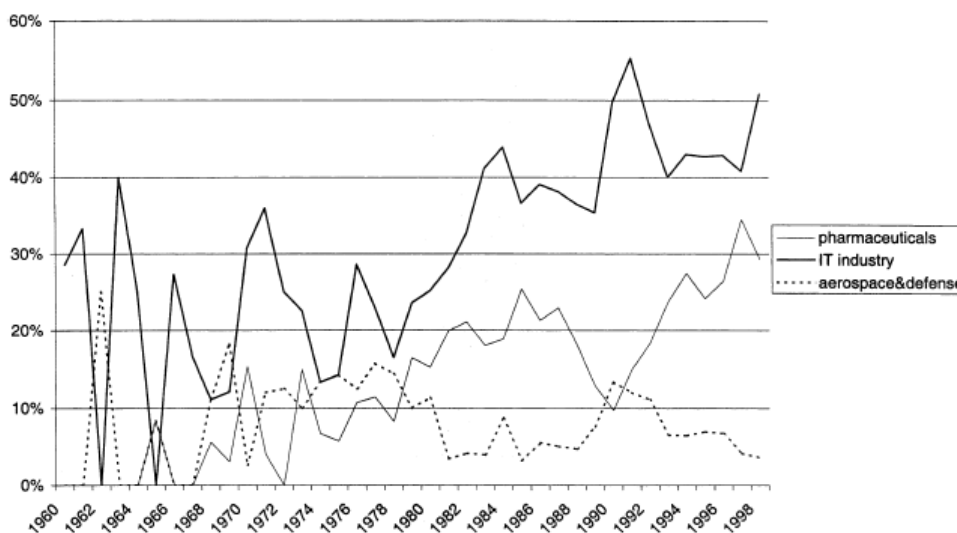


Figure 3: newly established R&D partnerships in high tech industries (percentages). Source: Hagedoorn (2002)



This simple quantitative evidence clearly shows the relevance of technological cooperation in the innovative process of high tech industries in their recent evolution.

2.2 What are the main reasons for technological cooperation?

Hagedoorn (1993) reports a list of main motives for firms to enter into interfirm technological agreements:

- i) Exploitation of technological complementarities
- ii) Performing basic R&D
- iii) High costs and/or risk of R&D
- iv) Lack of financial resources
- v) Reduction of innovation time span
- vi) Monitoring in new development of technology
- vii) Market access

Table 1 summarizes the relative importance of these motives for a selection of high tech industries:

Table1: motives for strategic alliances, sector and fields of technology. Source: adapted from Hagedoorn (1993).

	Technological complementarities	Basic R&D	Lack of financial resources	Reduction Innovation time span	Market access/structure	High cost/risks	Monitoring technology/market entry
Biotechnology	35%	10%	13%	31%	13%	1%	15%
New Materials Technology	38%	11%	3%	32%	31%	1%	16%
Computers	28%	2%	2%	22%	51%	1%	10%
Industrial automation	41%	4%	3%	32%	31%	0%	7%
Microelectronics	33%	5%	3%	33%	52%	3%	6%
Software	38%	2%	4%	36%	24%	1%	11%
Aviation/Defense	34%	0%	1%	26%	13%	36%	8%

Clearly, three motives stand up: technological complementarities, reduction in innovation time span and market access. In particular, I concentrate on the first aspect. In many high tech industries, innovation is more and more depending on different technologies and research areas. Firms cannot master all the different fields, and consequently they enter into collaborative agreements with other firms in order to innovate. In pharmaceuticals, for instance, after the new discoveries in molecular biology in the mid 70s, complementarities exist between economic and technological competences possessed by large pharmaceuticals firms and dedicated biotech firms. In microelectronics, innovation hinges on competences in fields as different as solid physics, construction of semiconductor manufacturing and testing equipment, and programmic logic.

2.2 What are the factors affecting knowledge transfer between collaborating firms?

In a knowledge-based view of the firm, technological collaborations are a means of interfirm knowledge transfer (Mowery, Oxley and Silverman, 1996). Under this respect, absorptive capacity (Cohen and Levinthal, 1989) plays an important role: to be able to absorb effectively new knowledge in a determined field, firms need existing knowledge in that field. This has two consequences for the effectiveness for knowledge transfer in a collaboration: first, in-house R&D has to be seen as complementary, rather than substitute, to R&D partnership, and more generally a reason for increasing returns in knowledge accumulation exist; second, a certain degree of “technological overlap” between firms is required. The joint assumptions of technological complementarities as motive for collaboration and technological overlap (i.e. absorptive capacity) as prerequisite for absorbing knowledge from collaborators implies that successful agreements involved firm that are not technologically too distant nor too near (Noteboom, 1999).

In two works, Mowery, Oxley and Silverman (1996, 1998) have tested this proposition empirically. In particular, they find an inverted U relationship between two firms technological overlap and the likelihood of their forming an alliance. In the tension between similarity and complementarity, they also find that in some collaborations firms become “more similar” after collaborating. They claim that in

these circumstances firms collaborate to acquire new capabilities. We can notice that this kind of dynamics aspect, while reinforcing absorptive capacity, can reduce at the same time the scope for complementarities. In other circumstances, firms become “more technologically distant” after collaboration; these are collaborations in which firms aim to “access” capabilities of their collaborators, and consequently specialization is promoted.

Under this respect, interesting results are in Stuart (1998) and Stuart and Podolny (1996). They consider an empirical analysis of horizontal technological alliances in semiconductor industry. They characterize firms by “technological positions” through patent citation analysis. Two results are important to mention here: firms in “crowded” technological area (i.e, area of technological space where many firms are located) are more likely to form technological alliances; second, technological alliances are an important factor in explaining intertemporal movement in firms’ technological position.

Together to absorptive capacity at the technological level, the literature stresses the role of what have been called “cooperative capability” (Gulati, 1998) or “alliance capability” (Kale and Singh,1999). With experience, firms learn how to manage their collaborative ties; to develop interfirm knowledge sharing routines and funnel results inside the organization; to govern contractual arrangements where there is room for moral hazard and incompleteness; to initiate necessary changes in the partnership as it evolves over time. In their empirical work on the biotechnology sector, for instance, Powell, Koput and Smith-Doerr find that experience at managing ties has a positive effect on firm growth.

This “non-technological” aspect of knowledge transfer among collaborators is important since it stresses the difference between this form of interfirm knowledge transfer and other channels (in particular, through unintended spillovers) and it reinforces an important point: outcomes of collaborations, in terms of learning, are generally asymmetric.

2.3 *Network perspective on strategical alliances*

Since there is a strong industry-effect in the adoption of technological interfirm agreements as innovative strategy, a network perspective, where each alliance is to be seen in the broader perspective of all present and past alliances (Gulati, 1998), can be profitably adopted.

In this field, work by sociologist is particularly important. Under a social network analysis perspective, innovation in an industry is seen as the result of an activity involving a network of actors (firms, but possibly also other types of organizations) linked each other. Firms are characterized by different *roles* and different *statuses*. This affects both the performance of firm in the network, and the evolution of network over time.

We can distinguish two broad categories of studies: a first class is more focused on the firm level, on motives and effects for firms to be in different position in the network; a second class of studies, instead, is more concerned with the overall structure of the network and its evolution over time.

In the first class of studies, centrality is usually supposed to be an important attribute of a firm. Centrality is a measure of how well connected the firm is in the overall network. Centrality in the network allows a firm to be aware of new technological developments and it is the way in which firms develop relational capability. In their sample of biotechnology firms, Powell, Koput and Doerr find that centrality is a good predictor of growth.

Centrality is also related to status formation (Stuart, 1998 and 2000). In an innovative context, a firm has a high status if it realized breakthrough innovations in the past. High status firms are more likely to form news links, since low status firms can give an external signal (for instance to financial markets) by collaborating with high status firms. In his study of semiconductor industry, Stuart (1998, 2000) shows that high status semiconductor firms (as determined by citations of their patent portfolio) are more likely to form new links and that small and young firms benefits more from large and innovative strategic alliance than old and large firms.

From a broader view point, a small number of studies apply tools of graph theory to networks of firms. Riccaboni e Pammolli (2001) perform a graph theory analysis on a network of biotechnology firms; Breschi and Cusmano (2002) do the exercise on the network of firms and research organizations resulting from EU-sponsored R&D consortia; Krebs (2002) analyses the case of the Internet Industry. These studies shows that innovative networks exhibit the “small world” property: high clustering and short average distance. This structure, which is very common in natural and social network, is driven by the presence of focal actors, having a significantly higher number of links than the average firm. A strong form of self-reinforcing mechanism seems at work in network evolution: organization with more links at time t are more likely to form new links at time $t+1$.

Broadly speaking, these empirical studies and their appreciative interpretation suggest a *co-evolutionary* view (Koza and Lewin, 1998) of firms’ attributes (technological positions, absorptive and relational capability) and network of collaborations. The model described in section 4 is an attempt to give a formal and simple representation of this co-evolutionary process, and to study mainly through simulations its properties.

3. Theoretical formal models of technological cooperation

Together with appreciative theories from the resource- and knowledge-based theories of firm, formal models have discussed, from different perspectives, the topics of technological collaboration and knowledge transfer among firms. Four main classes of models can be individuated. These are summarized in Table 2: in a very rough way, they can be allocated to the realms of “mainstream” and “evolutionary” economics.

Mainstream economics	Evolutionary economics
R&D cooperation in oligopoly: Katz (1986), D’Aspremont Jacquemin (1988), Suzumura (1992), Kamien and Zang (1992), Kamien and Zang (2000)	Self-organising networks: Saviotti and Pyka (1999), Gilbert, Pyka, Ahrweiler (2001), Riccaboni, Pammolli (2001).
R&D network games: Goyal and Moraga (2001) , Goyal and Joshi (2002)	Knowledge barter and diffusion on a network: Cowan and Jonard (1999,2000).

i) R&D cooperation in oligopoly

This is by far the largest (and still growing) body of literature (for a survey see de Bondt (1996)). Although previous relevant contributions to this topic (Katz,1986), the seminal paper for most of the following developments is d'Aspremont and Jacquemin (1988). They consider a simple framework of duopolistic Cournot competition, where at a pre-competitive stage firms can exert a cost-reducing effort. Spillovers exist, in the sense that effort exerted by firm 1 reduces marginal cost of firm 2, but this spillover effect is imperfect, i.e. the cost reduction for firm 2 is only a fraction of such effort.

In this paper, we find most of the elements that have become typical of this stream of literature. First, the rationale of cooperation is individuated in the existence of spillovers in R&D, which creates an externality. Cooperation is intended to internalize such externality. Second, R&D levels from cooperation can be higher or smaller than without cooperation, depending on several factors, and in particular on spillover rates and degree of market competition.

An impressive number of extension of this basic model has followed, considering different kind of regimes in market and R&D competition and different forms of cooperation. Kamien, Muller and Zang (1992) consider the role of information sharing together with coordination of efforts in cooperation; Kamien and Zang (2000) introduce a role for absorptive capacity and make endogenous the choice of a path (generic or specific) for research; Banerjee and Lin(2001) consider the case of vertical R&D joint ventures; De Fraja (1993) consider the case of a patent race as a model of R&D competition.

ii) R&D network games

Two papers (Goyal and Moraga, 2002; Goyal and Joshi,2002) consider explicitly the network structure of collaboration, relying on the literature on network games (Jackson and Wolinski,1996). The structure of these models is similar to that one of models discussed in the previous section: in the first period firms form collaborative links, and then they compete in the product market. Goyal and Moraga consider an endogenous choice of cost-reducing effort, while in Goyal and Joshi there is a automatic reduction in costs for linked firms.

The main emphasis of such models is on the comparison of stable networks (in which no firm has the incentive to form a non existing link, or to sever an existing one) and efficient networks (from the firms' or the society's view point). Again, spillovers among firms (that can possibly occur only among linked firms) and intensity of competition turn out to be relevant parameters for stability and efficiency of R&D networks.

My model is a dynamic extension of the model by Goyal and Joshi. Then, this model and its limitations are discussed more at length in the next section.

iii) Self-organising network

Formation and evolution of innovative networks have been studied as example of self-organising system. This is much in spirit with the co-evolutionary view of technological collaborations and innovative networks proposed in the previous section. This is a very recent bunch of literature, where attempts to systematize are still to make.

Gilbert, Pyka and Ahrweiler (2001) develop a general simulative model of innovative network. They consider a population of boundly rational agents (i.e, firms, universities or other research organization) with an heterogenous knowledge base. Agents can follow different strategies to innovate, in particular they can perform independent R&D or cooperate with other firms. This general model has been applied to study specific sectors. For instance, Pika and Saviotti (2001) analyse through simulation the case of biotechnology in history-friendly fashion (Malerba et alii, 1999).

Other similar approaches have been proposed. Pyka and Windrum (2001) use the Master-equation approach from statistical mechanics to study a simple model of R&D networks. Together with their empirical analysis, Riccaboni and Pammolli present a simulative model of network growth in biotechnology, calibrating parameters to fit the real data.

iv) Knowledge barter and diffusion:

A last small class of contributions address the related topic of knowledge barter and knowledge in a simulative model (Cowan and Jonard, 1999 and 2000). In these

model agents are located on a graph. They are endowed with different knowledge bases, and they can barter knowledge when it is mutually convenient. However, exchange is limited to agents who are directly connected in the network. The main goal of the analysis is to map the exogenously given structure of the network into the aggregate performance of the system (measured in terms of average level of knowledge in the economy). The result is that a network exhibiting the small world property is the most efficient one. The model has been used to study the phenomenon of collective invention (Allen, 1983), which is not so different from the network as locus of innovation discussed here.

The simulative models discussed in sub-section 3 and 4 are natural formal (and more rigorous) translation of verbal arguments following empirical analysis. Nevertheless, simulation techniques still lack a consolidate and rigorous theoretical framework, and transparency and interpretability of results are not always an easy task to accomplish. On the opposite, game theoretic techniques of models in sub-section 1 and 2 can formalize specific aspects of R&D cooperation (in particular, the interplay between market competition and R&D cooperation), but there are at odds with the co-evolutionary, self-organizing view.

4. The model

The model describes the evolution of an industry where firms can introduce process innovations through collaboration in an R&D activity, while remaining competitors in the market side. Firms are different from the technological point of view and this allows complementarities to be exploited through collaborations.

I consider a discrete sequence of periods $t=0,1,2,\dots$. Each period can be divided in two sub-periods: the *networking* phase, where firms can modify the network structure according to a procedure described below, and a *market competition* phase, where firms, given the network structure, compete in the product market. First, I characterize market competition, and then I discuss network formation and the effects of collaboration of firms.

4.1 Market competition

In the market n firms produce an homogenous product. I define as N the set of all firms. Inverse demand for such a good is assumed to be linear:

$$p = A - Q \quad (1)$$

where Q is total quantity produced by firms. Firms are characterized by zero fixed costs of production and constant marginal costs c_{it} , where i is the index for firm and t the index for time. Consequently, gross profits are given by: $\Pi_{it} = (p - c_{it})q_{it}$. Furthermore, each firm is characterized by a technological

position $\alpha_{it} \in (0,1)$. This is not affecting directly the level of marginal costs, but it is crucial in determining the value of collaborations. Firms compete à la Cournot, and it is assumed that firms play the (unique) Nash equilibrium in each period. This means that quantity produced in equilibrium by each firm is:

$$q_{it}^* = \frac{a - nc_{it} + \sum_{j \neq i} c_{jt}}{n+1} \quad (2)$$

Consequently, gross profit in the per-period equilibrium are given by $(q_{it}^*)^2$.

4.2 Network decision

At each moment t , the industry is characterized by an R&D network g_t . We define a binary variable $g_{ijt} \in \{0,1\}$: when $g_{ijt} = 1$, a collaborative link exists between firm i and j at time t . The network g_t is then a collection of states for the pair-wise relationships among firms. I indicate with $g + g_{ij}$ the network obtained by replacing $g_{ij} = 0$ in network g with $g_{ij} = 1$, and similarly with $g - g_{ij}$ I denote the network obtained by replacing $g_{ij} = 1$ with $g_{ij} = 0$. Furthermore I define $N_t(i) \equiv \{j \in N / \{i\} : g_{ijt} = 1\}$, that is the set of firms that have a collaborative link with firm i at time t .

A given network structure leads to a deterministic reduction in costs. In particular, I define the following variables, and the relationships linking them:

$$\gamma_{it} = \frac{1}{1 + \exp(C - L_{it})} \quad (3)$$

$$L_{it}(g_t) = L_{it-1} + \sum_{j \in N_t(i)} f(d_t(i, j)) \gamma_{jt-1} \quad (4)$$

$$c_{it} = c(1 - \gamma_{it}) \quad (5)$$

In words: γ is parameter measuring the efficiency of a firm. Efficiency is increased only through collaborations with other firms. For a given firm, a collaboration has a value which is 1) increasing in the level of efficiency of the collaborator 2) increasing in the value assumed by the function f , which depends on the technological position of firms involved in the collaboration. More specifically, the following notion of technological distance between firms is introduced in the technological space:

$$d_t(i, j) = |\alpha_{it-1} - \alpha_{jt-1}|$$

As discussed in section 2, firms need to be technologically “not too distant nor too near”. This is reflected by the shape of f , which is assumed to be a parabola (Cusmano, 2002):

$$f(d_t(i, j)) = a + bd_t(i, j) + cd_t(i, j)^2 \quad (6)$$

$$a \geq 0, c < 0, a + b + c \geq 0$$

Varying parameters a, b, c we can characterize different technological environments.

A non linear relation between the total value of collaborations accumulated over periods (L_{it}) and efficiency (γ_{it}) is assumed (eq. 3).

Increasing returns in L in the first phase are a simple way to capture absorptive and cooperative capacities. Since in the model the only way to

improve efficiency is through collaboration, I cannot distinguish between them; but I can claim that the *existence* of absorptive and cooperative capacities justifies the convex part of the curve. Technological and cooperative experience are required for effective absorption from cooperation. At the same time, after a given threshold, decreasing returns in technological competences, absorptive and cooperative capacities accumulation justifies the concave part of the curve.

Each period, two firms are randomly chosen to possibly change their network state. Firms that do not collaborate can decide to form a collaborative link, firms already collaborating can sever the existing link. I assume that maintaining a collaborative link cost a firm a fixed cost F .²

Assume that at period t , the link ij (i.e the potential or existing link involving firms i and j) is randomly chosen to be updated. If $g_{ijt-1} = 1$, the link is severed if $\Pi_{it}(g_{t-1} - g_{ij}) \geq \Pi_{it}(g_{t-1}) - F$ or $\Pi_{jt}(g_{t-1} - g_{ij}) \geq \Pi_{jt}(g_{t-1}) - F$, while it is maintained in the opposite case³. This simply means that a firm wants to sever an existing link if profits without the link and the saving on the cost of maintaining the link are higher than the profits with the link. If $g_{ijt} = 0$, the link is formed if $\Pi_{it}(g_{t-1} + g_{ij}) - F \geq \Pi_{it}(g_{t-1})$ and $\Pi_{jt}(g_{t-1} + g_{ij}) - F \geq \Pi_{jt}(g_{t-1})$. If a link does not exist, it is formed when for both players the gain in forming the link is higher than the cost of maintaining the link.

Finally, I assume that through collaboration firms modify their technological position. In particular, based on (part of) empirical evidence, I assume that firms becomes in general more “similar” to their collaborators. Formally:

² F can be interpreted as the sum of contribution of firm to the joint R&D project (then a strong form of indivisibility is assumed), and coordination costs in collaboration. In the simplest version, F is constant over time and among firms. Nevertheless, in a more sophisticated version of the model, one can assume a time- and firm-dependent cost of collaboration. In particular that could conjecture coordination and congestion effect (F rises when a firm has a lot of collaborations), or a trust and relation specific effect.

$$\alpha_{ijt} = \rho \alpha_{ijt-1} + (1 - \rho) \sum_{j \in N_t(i)} \frac{\gamma_{jt-1}}{\Gamma_{it}} \alpha_{jt-1} \quad \text{if } N_t(i) \neq \{\emptyset\} \quad (7)$$

$$\alpha_{ijt} = \alpha_{ijt-1} \quad \text{otherwise}$$

$$\text{where } \Gamma_{it} = \sum_{j \in N_t(i)} \gamma_{jt-1}, \quad \rho \in [0,1]$$

Notice that the case of collaborations for “having access to new capabilities” can be (although imperfectly) studied as specific case when $\rho = 1$.

5. Discussion

As previously said, the model presented in section 4 is an extension of Goyal and Joshi (2002). In this section I briefly discuss their model. My aim is to enlighten the specificities you get when you extend their static model to a co-evolutionary dynamic framework. A comparison with their model will make clear the formal structure of my model. In particular, I will discuss informally some of its long-run properties and the nature of the stochastic process generating the network and market evolution.

5.1 Reversibility, irreversibility and path-dependance

In the simplest version of their model (as in my model), firms compete à la Cournot by offering an homogenous product. Firms can reduce their marginal costs by collaborating with other firms. In particular, marginal costs of firm i are given by $c_i(g) = c_i(\eta_i(g;1))$, where $\eta_i(g;1)$ is the subset of firms at geodesic distance 1 from firm i (that is, having a direct link with firm i).

Using a slightly modified version of the notion of stability discussed by Jackson and Wolinsky, they study which networks of collaboration are stable, and they compare it with efficient ones.

³ It should be straightforward to see that profits can be written as time-dependent function of the network. The proposed rule implies that agents are myopic, since they decide only on the basis of their current pay-off, but at the same time they are able to predict *correctly* marginal costs of their rivals one period ahead.

A given network (in the sense of Goyal and Joshi) is stable if *i*) every link in g yields strictly positive benefits *ii*) unformed links are not strictly profitable for the firms individually. Their model is static, that is they do not consider how the network is formed, and how a stable network is reached.

A dynamic approach to network formation is a quite natural approach to discuss the issue, in particular to determine which of possibly many stable networks is reached (if one is).

Jackson and Watts (2002) and Watts (2001) tackle this problem by proposing the kind of algorithm I discussed in previous section. They introduced it in the framework of models that share a crucial aspect: the effect of a link is assumed to *reversible*, in the sense that it ceases once the link is severed.

If the outcome for the agents in the network is seen in terms of learning (as it is in our case), *irreversibility* seems on the contrary a more reasonable assumption.

For that reason, in my model, once firms have reduced their cost through collaborations, they preserve the reduced cost when they sever the link.

An implication of reversibility is that if a network g' can follow a network g at time t (in the sense that a link exists such that its revision leads to g' from g), then g' follows g (for the same link) g at any time $t + k$. This property cannot hold when irreversibility is introduced. In my model, it can be that, given the same network in the previous period, a firm want to form a link with a certain firm, but after some periods, facing the same network, it is no longer the case. What happens between the two periods influenced the efficiency levels of firms and their technological position, so that the context of decision is changed.

In other terms, the evolution of the network (and consequently of the industry) is characterized by a *path- dependent behavior*.

5.2 The stochastic properties of the system

The model I present exhibits the Markovian property, once we defined the appropriate state space. Define $L_t \in \mathfrak{R}_+^n$ as the n -dimensional vector of variable L

for all the firms; define $\alpha_t \in (0,1)^n$ similarly, as the vector of all technological positions. Then it is easy to verify that the economy at time t is completely characterized by the state $\omega_t \equiv \{g_t, L_t, \alpha_t\}$. I define Ω as the (infinite) set of all possible states. Then, we have a Markov process, since:

$$P(\omega | \omega_t, \omega_{t-1}, \omega_{t-2}, \dots, \omega_{t-k}, \dots, \omega_0) = P(\omega | \omega_t) \forall \omega \in \Omega$$

We can characterize the set of absorbing states of the process. Let me define the set $\hat{\Omega} \equiv \{\omega' : P(\omega' | \omega') = 1\}$.

The following proposition, that I do not prove, holds:

Theorem 1

1. The generic element $\omega \in \hat{\Omega}$ is characterized by $g_{ij} = 0$ for every $i, j \in N$
2. The set is reached with probability 1 in finite time.

A simpler way to claim the same result is that every existing link will be severed with certainty, and from a given period onward, no new links are formed. The result is almost trivial: in the long run the benefit of a collaboration tends to zero, while costs of R&D collaboration are fixed. At a certain moment is no longer optimal to maintain any link or to form new ones.

While this result has been claimed for completeness, it is clear that the main interest is on the *transition* of the system. First, due to non-ergodicity, the evolution of the network affects the final position of firms (the stable state that is eventually reached) and consequently their long run performance.

Second, and more important, the depletion of innovative opportunities can take a very long time, so that the dynamics of the transition phase is interesting per se. The high tech sectors the model wants to study are typically industries with a lot of innovative opportunities to exploit: then we are almost *always* in the transition phase.

In the transition phase, the network can evolve in a complex way: relatively regular structures can persist over significant periods of time; “catastrophic” change can occur; different stages in the life cycle of the network can be observed. Numerical simulations are the tool to study this potentially rich dynamics.

6. Conclusion

Based on some recurrent themes from empirical analysis, I described a simple stylized model describing the evolution of technological collaborative networks as a co-evolutionary process. Through numerical simulations, I mean to give an answer to the following questions: what kind of networks are likely to emerge? How is the evolution depending on model parameters, in particular those describing the features of technology? Are they consistent with the observed empirical pattern (for instance, do we observe the “small world” property?).

Since the model is very simple and abstract, several extensions are possible. I think it is worth mentioning two of them. First, the algorithm of dynamic network formation can be modified in order to accomplish realistic feature of technological collaborative networks (in particular, different typologies of interfirm agreements). Robustness of the results in this respect is important. Second, allowing entry and exit firms can extend the set of possible exercises. R&D networks can constitute a significant barrier to entry and survival of new firms. Similarly, it can be conjectured that the exit of firms in relevant positions in the network can have important consequences on industrial evolution.

References

Allen,R. (1983) “Collective invention”, *Journal of economic behavior and organization*, **4**, 1-24.

Banerjee,S. and Lin, P. (2001) “Vertical research joint ventures”, *International journal of industrial organization*, **19**, 285-302.

Breschi, S. and Cusmano, L. (2002) "Unveiling the texture of a European research area: emergence of oligarchic networks under EU framework programmes", Cespri WP 130.

Cohen, W. and Levinthal, D. (1989) "Innovation and learning: the two faces of Research and development", *The Economic Journal*, **99**, 569-596.

Cowan R. and Jonard N. (1999), "Network Structure and the Diffusion of Knowledge", MERIT WP #99-028, Maastricht University.

Cowan R., Jonard N. (2000), "The Dynamics of Collective Invention", MERIT WP #00-018, Maastricht University.

Cusmano L. (2002), "Knowledge creation by R&D interaction: role and determinants of relational research capacity", mimeo.

D'Aspremont and Jacquemin (1988) "Cooperative and noncooperative R&D in duopoly with spillovers", *American Economic Review*, **78**, 1133-1137.

De Bondt, R. (1996) "Spillovers and innovative activities", *International Journal of Industrial Organization*, **15**, 1-28.

De Fraja, G. (1993) "Strategic spillovers in patent races", *International Journal of Industrial Organization*, **11**, 139-146.

Gilbert N., Pyka A. and Ahrweiler, P. (2001) "Innovation Networks-A simulation approach", *Journal of artificial societies and social simulations*, **4**(3).

Goyal, S. and Joshi, S. (2002) "Networks of collaboration in oligopoly", *Games and Economic behavior*, forthcoming.

Goyal, S. and Moraga, J. (2001) "R&D Networks", *RAND Journal of Economics*, **32**(4), 686-707.

Gulati, R. (1998), "Alliances and Networks", *Strategic Management Journal*, **19**, 293-317.

Hagedoorn, J. (1993), "Understanding the rationale of strategic technology partnering: interorganizational modes of cooperation and sectoral differences", *Strategic management Journal*, **14**, 371-385.

Hagedoorn, J. (2002), "Inter-firm R&D partnerships: an overview of major trends and patterns since 1960", *Research Policy*, **31**, 477-492.

Jackson, M and Watts, D. (2002), "The evolution of social and economic networks", *Journal of economic theory*, **106**(2), 265-295.

Jackson, M. and Wolinski, A. (1996), "A strategic model of social and economic networks", *Journal of Economic Theory*, **71**, 44-74.

Kale, P. and Singh, H. (1999) "Alliance capability and success: a knowledge-based approach", mimeo.

Katz, M. (1986) "An analysis of cooperative research and development", *RAND Journal of Economics*, **17**, 527-543.

Koza, M. and Lewin, A. (1998), "The Co-Evolution of Strategic Alliances", *Organisation Science*, **9**(3), 255-264.

Krebs, V. (2002), www.orgnet.com .

Malerba F., Nelson R., Orsenigo L., e Winter S. (1999). "History friendly' models of industry evolution: the computer industry", *Industrial and Corporate Change*, **8**(1).

Mowery D., Oxley J. and Silverman B. (1996) "Strategic Alliances and Interfirm Knowledge Transfer", *Strategic Management Journal*, **17**, Winter Special Issue, 77-91.

Mowery D., Oxley, J. and Silverman, B. (1998) "Technological Overlap and Interfirm Cooperation: Implications for the Resource-Based View of the Firm", *Research Policy*, **27**, 507-523.

Noteboom B. (1999), "Inter-firm Alliances. Analysis and Design", Routledge, London.

Pammolli, F. e Riccaboni, M.(2001) "Technological regimes and the growth of networks: an empirical analysis and a simulative model", mimeo.

Pyka, A. and Windrum, P. (2001) "The self-organization of strategic alliances", mimeo

Powell Walter W., Koput Kenneth W., Smith-Doerr Laurel (1996), "Interorganizational Collaboration and the Locus of Innovation: Networks of Learning in Biotechnology", *Administrative Science Quarterly*, **41**, 116-145.

Saviotti, P. and Pika, A. (2001) "Innovation Networks in the Biotechnology-based sectors", mimeo.

Stuart T. and Podolny, J. (1996), "Local Search and the Evolution of Technological Capabilities", *Strategic Management Journal*, **17**, 21-38.

Stuart, T. (1998) "Network Positions and Propensities to Collaborate: An Investigation of Strategic Alliance Formation in a High-technology Industry", *Administrative Science Quarterly*, **43**, 668-698.

Stuart, T. (2000), "Interorganizational Alliances and the Performance of Firms: A Study of Growth and Innovative Rates in a High-Technology Industry", *Strategic Management Journal*, **21**, 791-811

Watts, A. (2001) "A dynamic model of network formation", *Games and economic behavior*, **34**, 331-341.