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The Chemical Sectoral System. Firms, markets, institutions and the processes of knowledge creation and diffusion

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1. Introduction

The aim of this work is to describe the features of the chemical industry within the theoretical framework of sectoral systems of innovation and production, and hence describing its knowledge and technological base, existing complementarities among knowledge, technologies and products, the heterogeneity of agents, their learning processes and competencies, the role of non-firm organisations, and the presence of (co)evolutionary processes (Malerba, 1999). The heterogeneity of this industry, together with its one century history make this task difficult and interesting at the same time.

One the one hand, it results hard to reduce the different segments composing the chemical industry in one unique "sector", whatever defined. Each of them has specific features, faces different problems, is based upon specific knowledge and technological base, and require companies operating within to adopt different behaviours and strategies. Previous studies that have tried to describe the main characteristics of the chemical industry have widely emphasises the heterogeneity of the industry, and the several dimensions by which it can be studied (among others, see Landau *et al.*, 1998).

On the other hand, chemicals is certainly one of the oldest industries since the industrial revolution. The history of the chemical industry is certainly the history of large companies competing for size and small innovative firms, of relationships among firms and among non-firm institutions (such as universities), of internationalisation processes, and of conflict between policy regulation (e.g., in order to face environmental problems) and competition through market-based mechanisms (Aftalion, 1999). Compared to other fascinating, but younger industries (e.g., computers, semi-conductors or telecommunications) it can offer significant examples of possible evolutionary and co-evolutionary processes. For instance, processes of technology diffusion and transfer which are characterising the late development of the semi-conductor industry can be usefully compared with those operating in chemicals since the 1960s, and that gave rise to the market for process technologies.

However, one of the main features of the chemical sectoral system is the role played by the knowledge dimension, and processes of knowledge creation and exploitation. Mostly on this dimension has been played in the past and is played even today the competitive challenge between firms, and between countries and regions. It is true that firm size is important as well. Many chemical companies have to increase their size in order to sustain the big effort of marketing and reaching markets geographically dispersed, and in order to spread the huge fixed costs of plants' setting or product development. However, innovation often remain the real critical point. It is because of the efficient organisation of innovative activity and the strict links with universities and engineering departments that German chemical companies in the early XX century became world leaders. And is because of innovative effort that companies can efficiently compete in the new specialty products markets. Again, is because of the capability of producing "green" products and developing less pollutant process technologies that chemical companies can satisfy stricter and stricter limits imposed by environmental regulation.

Hence, after having described the main features of the sectoral system in chemicals – sector boundaries, agents and relationships among agents, geography of the sector and issues of international performances, industry dynamics and evolutionary patterns – this study will focus its attention mostly on describing the processes of creation, diffusion and use of knowledge and its structure. On the one hand, the analysis will take into consideration the processes of development of technological competencies, and of creation of technological knowledge. This phase is particularly important, because non-firm institutions, such as universities and laboratories, enter to play. Furthermore, in order to better explore these processes, the level of the analysis will be shifted in this case from the firm to the single inventors. In particular, the *organisational proximity* within the firm will be compared with the *geographical proximity* within the technological clusters, as organisational modes for producing innovations.

On the other hand, we will explore the processes of technology transfer and diffusion. Indeed, the chemical sectoral system is characterised by a dense network among different agents, both chemical firms, specialised suppliers and engineering firms. The objective of this network is to exchange technologies (mainly process technologies), and, in some sense, it is possible to observe the emergence of a market for (process) technologies. The actual functioning of this market is strictly linked with the licensing activity promoted by larger firms, and at the same time firms' decision to license out their proprietary technologies depends upon the existence of such a market. Hence, the understanding of firms technological strategies becomes important in order to analyse causes and consequences of the market for technologies in chemicals.

The study is organised as follows. It is mostly composed of two main parts. The first (sections 2 to 4), tries to describe the chemical industry by means of the framework of sectoral systems. Explicitly, Section 2 defines the general boundaries of the chemical sectoral system, in terms of its dimension, its tradition in innovation and R&D activities, the linkages between this sector and downstream sectors, and the innovative patterns existing in this industry. Section 3 explores the geographical dimension of the sector and addresses the question of whether it is useful discussing of international performance, and what factors play a role in this respect. Section 4 analyses the evolution of industry organisation, and of co-evolutionary processes, by paying special attention to the environmental topic.

While the first part is mainly descriptive, the second part reports some original empirical findings. It focuses its attention on processes of knowledge creation and diffusion. So, section 5 explores the phase of knowledge development. By means of a patent analysis, it compares the firm and the cluster as different organisational modes for producing innovations. Section 6 focuses on the processes of technology diffusion and licensing, after that innovations have been developed. After having discussed the conditions that brought to the upsurge of a market for technologies in chemicals, it provides some empirical evidence of the latter, and highlights the role of firms' licensing behaviour in the development of such a market. Section 7 concludes the paper.

2. Defining the boundaries of the sector

2.1 Industry structure and corporate strategies

The chemical sector is a large and heterogeneous sector (Cook and Sharp, 1992). The heterogeneity, the size of the industry, its scientific tradition, and the linkages with many other industries and products are important characteristics of the sector. They strongly influence industry structure and firms' technology strategies.

As for *heterogeneity*, chemical products range from bulk chemicals – or basic or commodity chemicals – to speciality chemicals. Basic chemicals are high quantity and low value-added products characterised by low differentiation. By contrast, speciality products such as dyes and paints, food additives and photographic materials are more differentiated and sophisticated products. They are also produced in low volumes, and sold for high prices. This heterogeneity mirrors completely different technological, scientific and R&D strategies by individual sub-sectors and firms.

As far as *size* is concerned, the chemical sector is today the largest manufacturing industry in the United States, and the second largest in Europe. It produces about 1.9% of the US gross domestic product and about 11.3% of US manufacturing value-added (Arora, Landau and Rosenberg, 1998). In 1999, the European chemical industry produced about 2,4% of the European gross domestic products, and contributed to the European total manufacturing production with a share of about 9.7%.[1] In terms of value added, the chemical industry ranked third within the EU manufacturing industry. The order of magnitude of these percentages is similar for Japan. From a global perspective, in 1996 the US chemical industry had about 24% of the global market. Japan was second with 14%. The market share of Germany and Britain was 8% and 4%, respectively. The rest of chemical production is spread across the rest of Western Europe and Asia. Twelve of the largest chemical multinational companies are European (Cook and Sharp, 1992).

Another important characteristic of the chemical sector is its *long tradition in innovation and R&D activities*. Since its origins in the second half of the XIX century with the British and German dyestuff manufacturers, the chemical sector is a science-based sector. Innovation in this industry derives from the interaction between the academic world, individual firms, government economic policies, and historical events. Empirical work has shown the importance of the linkages between internal R&D capabilities and external sources of scientific knowledge for successful innovation (among others, see Freeman *et al.*, 1963). Universities and small firms are key for carrying out basic research and developing product innovations. Firms' in-house R&D is the essential complement to exploiting external linkages. This strong linkage between university research and firms' innovative activity is particularly important even today, especially in new fields. Recent studies using patent statistics (Geuna, 2000), show that in emerging fields like combinatorial chemistry the contribution of basic research – from universities and other public research centres – to industrial innovation is essential. With consequences that will be better explored in the following sections, the strong interaction between academic research and industrial innovative activity clearly influences international performances. In the case of combinatorial chemistry, the US lead in firm formation is paralleled by the dominant role played by US universities and research centres. While EU countries are catching up in terms of university publishing, the number of new combinatorial synthesis firms in Europe remain very small. Hence, the inventive capacity of a country heavily depends upon the strength of the underlying universities and public research institutes.

Private firms were also the major source of R&D funding and the locus of technological applications. Today, the firm average R&D intensity in the chemical sector is about 5%, which is higher than the average R&D intensity in other sectors. In fields like pharmaceuticals and biotechnology, firms' R&D intensity may exceed 20%. All the major technological innovations in the 1920s and 1930s – such as polystyrene, perspex, PVC, polyethylene, synthetic rubbers, nylon and other artificial fibres – were developed in the laboratories of

[1] See the European Chemical Industry Council (CEFIC) web page: http://www.cefic.be/activities/eco/ff99/01-11.htm.

large chemical companies, most of which still exist today (e.g. DuPont, Bayer, BASF, Hoechst, and ICI, among the most influential).

Another important feature of the chemical industry is that more than 50% of *chemical products are intermediate goods* used by a wide range of industrial sectors (Albach *et al.*, 1996). More than 70,000 products like paints and coatings, fertilisers, pesticides, solvents, plastics, synthetic fibres and rubber, explosives and many others are building blocks at every level of production and consumption in agriculture, construction, manufacturing, and in the service sectors. Put differently, the chemical sector is the upstream sector providing intermediates for several downstream users. Moreover, since successful innovations have positive effects in many downstream industries, the chemical sector is also an important source of knowledge spillovers and technology diffusion.

The *strategies and the innovative decisions of chemical firms* are dependent upon the characteristics of the branch of the industry in which they operate. For example, products heterogeneity leads chemical firms to follow strategies of cost leadership or specialisation depending upon the products being produced (Porter, 1985). Firms adopt a cost leadership strategy in areas characterised by price competition. This is the case of basic chemicals. By using information drawn from the Community Innovation Survey, Albach *et al.* (1996) show that during the past few years, European firms in commodity chemicals focussed on cost leadership strategies. In so doing they increasingly concentrated in their core areas, and engaged in strategic alliances with other companies. By contrast, firms in the specialty sectors tended to pursue specialisation strategies characterised by great product differentiation and customisation, and higher profit margins.

In turn, the decision to follow cost leadership or specialisation strategies influences firms' innovative behaviour. Cost leadership leads companies to promote process innovations in order to reduce the cost of production. By contrast, specialisation strategies require companies to focus on product innovations, in order to better respond to customers' needs, and to set higher prices. Albach *et al.* (1996) show that in agrochemicals, paints and varnishes – i.e. speciality products – more than 60% of firms allocate at least 75% of their R&D budgets to product innovations. The share of companies devoting 75% of total R&D expenditure to product innovation falls to about 30% in basic chemicals. However, firms producing basic chemicals spend about 75% of their R&D budget on process innovations. This survey also suggests that companies are increasingly entering into strategic alliances in the area of R&D, both with other firms, and with academic and research institutions. Again, however, the use of cooperative arrangements varies according to the sector. Companies from the agrochemical sector have the highest propensity to R&D collaboration. The opposite holds for firms in soap and detergents. Cooperation with universities, government laboratories, and other research institutions is frequent for companies from basic chemicals and man-made fibres.

2.2 Sectoral innovative patterns

The existing studies on the chemical industry highlight the long tradition in innovation and R&D in the sector (see, for example Landau *et al.*, 1998). This section describes how discoveries and innovations are developed in the chemical sectoral system, and illustrate the organisation of the innovative process and its evolution over time. It also discusses how "upstream" features of the industry affect firms' strategies and industry structure. Notice that industry structure, firms' strategies and behaviour, and the organisation of innovative activities of today are the result of the evolution of the industry over one century history.

Hence, to fully understand the modern chemical industry it becomes essential to recall the main past events, whose effects are visible yet today.

The modern chemical industry started in Great Britain in the first half of the XIX century, when the first inorganic chemical firms emerged. However, although the industry started by producing inorganic products – such as soda, soda ash and blench – the engine of growth was represented by organic chemistry, particularly dyestuff. As a matter of fact, due to the rapid pace of technological change in organic chemistry, firms changed their approach to innovation. They started to adopt innovative strategies based on the methodical application of scientific discoveries to chemical manufacture.

The ***synthetic-dyestuff model*** is a meaningful example of the new approach to innovation. Its main feature is the use of the scientific base for developing new products and processes. Advances in the scientific principles governing organic chemistry provided a good understanding of how carbon atoms were linked to hydrogen and other atoms to form complex molecules. This knowledge was the beginning of the development of a "general purpose technology" based upon the idea that different chemical composites could be designed by using the scientific background on the properties associated with atoms, and bounds among atoms.

The direct implication of the synthetic-dyestuff model was the possibility of exploiting economies of scope in knowledge: a common scientific base on atoms and bounds properties was the necessary background in order to develop different organic products. Firms that could master this knowledge had a strong incentive to diversify their product portfolio in sectors that share the common scientific base, like pharmaceuticals, explosives, and photographic materials.[2]

A second implication of the application of the synthetic-dyestuff model has been the resurge of the role of universities and other scientific research institutes. Being the synthetic-dyestuff model a science-based model in which the invention of new products was strictly dependent upon advances in the scientific understanding of the chemical structure of new molecules, the largest and most innovative firms established strong links with the academia. Chemical companies began to recruit researchers in the universities, and promoted research collaborations aimed at inventing new products. They also applied for joint patents, and promoted alliances with universities to set up special research institutes (Murmann and Landau, 1998).

However, the synthetic-dyestuff model was only the beginning of the science-based approach to innovation in chemicals. The continuation of the synthetic-dyestuff model was ***polymer chemistry***. Initiated by Herman Staudinger and other German scientists in the 1920s, polymer chemistry is based upon the idea that any material consists of long chains of molecules – i.e. polymers – linked together by chemical bounds. The scientific understanding of the existence and configuration of these long chemical macromolecules led to the principle of "materials by design" (Arora and Gambardella, 1998). According to this principle, it exists a relationship between the characteristics of the macromolecular structures and the proprieties of materials. This means that the scientific understanding of chemical composites is the base for different product applications.

[2] This was the case of Hoechst, that in 1883 produced the pain-relieving Antipyrin, and Bayer, that in 1899 patented the pain-relieving, fever-reducing, anti-inflammatory Aspirin. AGFA used the same technological convergence of some organic intermediates and in 1887 diversified in photochemicals.

As in the case of the dyestuff model, the rise of polymer chemistry strongly influenced the evolution of the chemical sector in the post-war era. The reasons are twofold. First, polymer chemistry provided a common technological base for developing applications and product differentiation in five distinct and otherwise unconnected product markets – i.e. plastics, fibres, rubbers and elastomers, surface coatings and paintings, and adhesives. This lowered the amount of time and research needed for product innovation in the sector. But, if the use of abstract principles governing the macromolecular structures offered the solution to "how" to innovate, the question shifted to "what" to produce. In other words, while the process of producing new products was comparatively easier for any chemical firm, the discovery of the "right product" was not. Competition among firms shifted to the correct anticipation of the users' requirements, and to the development of the most suitable applications. This meant that, to innovate successfully, firms had to become knowledgeable about the characteristics of different market segments. To do so, they developed extensive linkages with the downstream markets.

Second, the new opportunities created by polymer chemistry were exploited by a large number of companies world-wide which had the required size, the scope, and the in-house expertise to exploit it. As Freeman (1982) points out, the presence of a large number of firms with comparable capabilities in polymers implied that even "small" information leaks allowed very rapid imitation. Many chemical companies and some oil producers found themselves competing in very similar markets.[3] The increased competition in almost every market segment led to a renewed attention to product differentiation and commercialisation strategies as important sources of competitive advantage. This encouraged extensive investments in R&D to develop new product variants, and systematic linkages with the users in order to tailor products for specific applications.

The shift from coal to petroleum hydrocarbons, started in the years before the Second World War in the US, was the main reason for a new, radical change in the innovative patterns in chemicals. Indeed, the world-wide diffusion of petrochemical technologies was strongly due to the upsurge of chemical engineering.

The concept of ***unit operation*** presented by Arthur D. Little to the Corporate of MIT (Massachusetts Institute for Technology) in 1915 was key to the development of chemical engineering. The idea of the unit operation consists in the breaking down of chemical processes into a limited number of basic components or distinctive processes that are common to many product lines (Wright, 1998).[4] This abstract and general concept became the "general purpose technology" of the chemical sector, and provided the unifying base for more contextualised and problem-solving innovations at the plant level (Rosenberg, 1998). Furthermore, it made possible to separate product innovation from process innovation, hence leading to important changes in the organisation of the chemical sector.

First, process technology was made into a commodity that could be traded.[5] This allowed chemical technologies to diffuse rapidly and easily. Strong economies of specialisation were

[3] For instance, Union Carbide, Goodrich, general Electric, IG Farben, and ICI were all doing research in PVC and producing the polymer. Dow, IG Farben, and Monsanto were all involved in the polystyrene business. Du Pont, ICI, Union Carbide, Monsanto, Kodak, and many other firms invested in other types of polyamides, acrylics and polyesters (Spitz, 1988; Aftalion, 1989).

[4] See Rosenberg (1998) for the discussion of the "unit operation", and the role of MIT in the development of the chemical engineering discipline.

[5] This point will be discussed in Section 6.

achieved at the industry-level, and a large number of vertical linkages were developed between chemical companies and Specialised Engineering Firms (hereafter SEFs). These vertical ties often resolved into partnering relationships of two types: between the SEFs and a number of chemical firms developing new technologies; and between the SEFs and an even larger number of firms buying these new technologies. As Freeman (1968, p.30) points out, in the period 1960-1966 "(N)early three quarters of the major new plants were 'engineered', procured and constructed by specialist plant contractors", and the SEFs were the source of about 30% of all licenses of chemical processes. By supplying the necessary process technologies, the design and the engineering know-how of new plants, the SEFs facilitated entry of new firms into the chemical industry after the Second World War, and allowed other countries such as Germany to catch up quickly in petrochemicals.

A second effect of the introduction of the unit operation concept and the rise of the chemical engineering discipline was the renewal importance of university research for developing innovations. The academic research assured the orientation toward general results. The link of the university with the industry, and its partial dependence upon private industry funding, assured the focus on industrial needs. Moreover, in order to develop many processing technologies, and to achieve meaningful results, chemical engineers needed the large scale operations of the chemical firms, that the university alone could not supply.[6]

This interaction between profit-seeking institutions and independent or semi-independent professional scientists influenced the evolution of technology in engineering discipline. Threatened by the possibility of going to the academy as a potential employment option, firms often had to adapt their employment conditions to match those typically found at the university. In so doing they allowed a certain degree of freedom and flexibility to chemical scientists and engineers, and gave the possibility to publish their research achievements. In the US, this might have limited corporations' ability to appropriate knowledge, and to channel new technologies. By contrast, Germany resisted chemical engineering as an autonomous discipline until the 1960s, and drew a clear demarcation line between subjects to be studied at the university, and those of more immediate usefulness of the industry. Also the British ICI showed limited interest in university-trained engineers up to the Second World War. Only when Britain entered the refining market, the demand for chemical engineers grew rapidly.

To sum up, the three examples of synthetic-dyestuff, polymer chemistry and unit operation along with chemical engineering illustrate how the organisation of innovative activities in chemicals has relied on the application of general scientific knowledge to the discovering of new products and processes. This approach to innovation has let to major changes in firms' strategies and market structures, some of which have been explored in this section.

3. Geography of the chemical sectoral system and international performance

In analysing the geographical dimension and international performance of the chemical industry one cannot forget that the chemical industry has always been "global". This means

[6] An important example of university-industry networks in this period is that between the New Jersey Standard and the MIT at the research facility in Baton Rouge, Louisiana (Landau and Rosenberg, 1992). The PhD degree came to play a role in chemical engineering much earlier than in other engineering disciplines. No longer after the beginning of the discipline, the enrolment of graduate students in chemical engineering grew rapidly. At the time of the presentation of the "unit operation", the consulting company of Arthur D. Little employed a large number of MIT graduates.

that not only the national dimension might not be relevant in the analysis of competitiveness, but the multinational dimension (Europe vs. US, for example) might not be enough as well.

The "global" dimension of the chemical sector can be analysed in terms of investment flows. For many years the industry has shown considerable flows on international investments, and systematic flows of engineering and process licenses. While up to the 1980s foreign investments were to a large extent confined to first world countries, in the recent decades there has been an increase in the flows towards the developing countries as well. As a matter of fact, chemical investments in these countries have become a critical strategy of the major multinational chemical firms from the advanced world, and to some extent the ability to invest in these countries has become a major factor in enhancing their competitiveness, and more generally an important element for competition in the industry. Moreover, apart from foreign direct investments in plants, the developing countries have become important areas for inflows of process licenses and engineering services. Again, the competitiveness of the chemical firms in advanced countries is often related to their ability to operate and invest in these markets, as well as on their ability to complement these investments with related technology flows through licenses or engineering services.

While this trend has characterised chemical companies both from Europe, the US and Japan, it seems that European companies have benefited more of international investments. The European chemical industry ranks first in the world in terms of turnover, but there is a considerable concern the European industry is loosing ground. The smaller and more fragmented European market have encouraged European firms to invest abroad, while facing high labour cost in Europe.

Analyses of investment flows (Arora, Garcia-Fontes and Gambardella, 1998) show that the European chemical industry has indeed moved abroad its investments. However, the same can be said for the American and Japanese chemical industry. This means that there has been an increasing globalisation process for this industry, that can be translated into a significant increase in the number of chemical plants built in Asia, coupled with a decrease of the domestic share of Japanese of the domestic share of Japanese firms in Japan, American firms in the US and European firms in the European Union. In general, it can be said that there is a trend toward the location of plants near the customers and the fast-growing regions, where the demand and consumption may be stronger. This trend might be related to an increase in product differentiation and customisation of plants, together with an increased concern on reducing transport costs. However, as far as the European dimension is concerned, there is some evidence that the process is stronger for the chemical firms from the European Union. These firms have been major actors in the increase in investments in Asia, and in the reduction of shares for domestic firms in the US and Japan. Indeed, the trend for the location of European firms in North America, Japan and Asia is stronger than the trend of American and Japanese firms locating in Europe.

In terms of products, the main products for the shift of investments to Asia have been Organic Chemicals Refining, Petrochemicals and Plastics & Rubber. In general, during the 1980s, the largest share of plants belonged to Organic Chemicals Refining, while during the 1990s, it shifted to Plastics & Rubber and Petrochemicals.

The sectoral dimension of globalisation process is particularly important. The case of specialty chemicals is representative in this respect (Sharp, 2001). In specialty chemicals, what were national companies competing as oligopolists in predominantly national or regional (e.g., European) markets have become international companies competing against each other in the global market place. This has important implications. The process of specialisation via merger and acquisition – consider the de-merger of Zeneca from ICI, the merger o Zeneca with Astra, of Ciba Geigy with Sandoz, of ICI with Unilever, of Hoechst with Rhone Poulenc – has essentially meant that what was national or regional oligopoly has been transformed into global oligopoly. In each sector, competition involves no more than six to twelve large firms that dominate the market, but that market place is now global. New entrants need to compete both in terms of scale and marketing, but, because of the size on incumbents and their financial and organisational strength, it is in marketing that new entrants find it most difficult to compete. This means that, in spite of intense global competition, it is still possible for one or two firms to dominate in each national market place, because they possess dominant complementary assets in marketing and effectively control access to consumers.

Hence, what does international performance means? How can be assessed the importance, or competitiveness, or performance of the chemical industry at the national level? In general terms, it seems that countries or regions' performance and competitiveness is strictly linked to the presence of large multinational companies, which, in turn, is related to the presence of national or regional characteristics involving local demand, research capabilities, and scientific and technological knowledge base. Large firms move and locate their production plants and their R&D facilities according to the presence of these factors. Consideration on investments flows reported above respond to this scheme. On a different dimension, the comparison between US and European chemical industry can also be conducted in terms of the respective capability of translating public research in commercial innovations. Of course, differences emerge in this respect in sub-sectors also within the chemical industry.

The considerations discussed above on combinatorial chemistry and environmental technologies go in this direction. Moreover, in the agrochemical industry, the current discovery process of new agrochemicals requires the integration of various distinct scientific disciplines. Europe shows a healthy publication level in fields necessary to the agrochemical sector. However, patent levels and the number of products introduced is low indicating that Europe has difficulty in bringing its research to market. Contrary to scientifically more dynamic industries, in paints, coatings and printing inks industries, European firms seem in a better position. For instance, from a technological point of view, the industry seems to be perfectly capable of coping with the diffusion of new, solvent free formulations, although it is quietly difficult to find differences between US and EU firms. In the new materials subsector the research effort is mainly public, as the private sector seems to wait for commercial potential. However, large firms have been the main source of incremental innovation with an important cumulative impact. These incremental developments are coming from the laboratories of these large firms, although frequently working in conjunction with users and/or outside specialists from academia or specialist firms, with differences among countries in the availability of these two factors. In sum, the scientific and technological base plays a key role in defining competitive positions of different countries and regions in different sub-sectors, because they represent a strong incentive for large multinational companies to locate in specific national boundaries.[7]

[7] As reported by Sharp (2001), "the presence of Hoechst, Bayer and BASF, together with the close competition from Sandoz, Ciba Geigy and Hoffman la Roche in Switzerland, was seen to provide the basis for the comparative (competitive) advantage of Germany and Switzerland in chemicals and pharmaceuticals. Britain's support for a 'cluster' of pharmaceutical firms was likewise seen to have brought the UK competitive advantage in this sector". However, "[n]ational competitiveness can be seen not so much in the performance of nationally-

In this sense, national policies might play a partial role. If they are capable of providing education, training and an infrastructure supportive to science-based industries they will be capable of offering a critical contribution to this kind of competitiveness, because they will create the conditions by which MNEs might decide to locate some of their divisions. Regions that will be able to become centres of information, communication and knowledge application will attract more knowledge-intensive MNEs (Meyer-Krahmer, 1999). Examples of Ireland and India in the case of software and semi-conductors are representative of this pattern.

4. Evolutionary and co-evolutionary processes

4.1 Industry dynamics: the evolution of networks formation

One of the possible solutions for describing the dynamics of industry structure is to move from a firm-level to a network-level approach. Linkages among firms, research institutions, and users are an important feature of the chemical sector. Their characteristics evolved and influenced the evolution of the industry according to the specific historical circumstances. Although inter-firm networks, university-industry networks, and user-producer networks are common to any period, each of them is mainly associated to specific historical events. This is because they aim at achieving different objectives. Inter-firm networks include firm-to-firm strategic agreements for R&D, production and marketing. University-industry networks are firm-to-academy linkages aimed at developing basic innovations. Finally, user-producer networks are linkages that firms develop in order to be responsive to their customers' needs, especially in the more downstream specialty sectors.

During the XIX century, when the synthetic-dyestuff model emerged, the invention of new products was strictly related to some advances in scientific understanding of the chemical structure of new molecules. The role of universities and other scientific research institutes was extremely relevant. The largest and most innovative firms established different links with these agents. A type of university-industry interaction was the recruitment of researchers in companies' organisations. But many other different kinds of links were promoted like research collaborations aimed at inventing new products, and applying for joint patents.

At the same time, the dyestuff model imposed the establishment of strong interactions between firms and users, not only for technical reasons. The strong interaction with the users allowed dyes firms to better understand customers' needs, and produce products better suited to a diversified demand. R&D activity benefited widely from this type of interaction, a continuous stream of product innovation could be ensured, and chemical firms could achieve a competitive advantage.

The World War I brought deep changes in the structure of the international chemical industry, and in the behaviour of firms. In order to satisfy the war needs, governments played a strong influence on the demand side of chemical products. The demand for explosives, drugs, and fertilisers during the war allowed chemical firms to utilise completely their production capabilities. But, when the war stopped, and the reconstruction period ended, the demand for chemical products decreased in all countries. Most chemical producers suffered during the inter-war period of overcapacity problems, that imposed a rationalisation of the whole

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based MNEs, as in the degree to which international companies are drawn to locate within national boundaries, and the quality of the jobs they bring with them and attract to them".

chemical industry. The increase in the number of mergers, acquisitions (e.g., IG Farben in Germany, and of ICI in Britain) and cartels (e.g., the Nitrogen Cartel between IG Farben and ICI) was the natural response to the pressures for cost reductions in all countries. Networks in this period became synonymous of collusion.

After the World War II two major technological breakthroughs influenced the formation of networks and industry structure. We already explored these changes from the technological viewpoint in the previous section. On the one hand, polymer chemistry encouraged the formation of networks between producers and users of chemical products. Indeed, competition among firms shifted to the correct anticipation of users' requirements, and to the development of the most suitable applications. This meant that, to innovate successfully, firms had to become knowledgeable about the characteristics of different market segments. On the other hand, chemical engineering encouraged the formation of university-industry linkages, and the development of vertical networks between chemical companies and specialised process design and engineering contractors (SEFs). In turn, the process of increasing specialisation and cumulative learning in process design was the basis of SEFs' comparative advantages in developing this "market for chemical technologies". They supplied the necessary process technologies, the design and the engineering know-how of new plants. As a consequence, the chemical industry resulted in an increasing division of labour at the industry level between SEFs and chemical manufacturers.

A final discontinuity in industry dynamics can be observed during the 1980s. The rise of the SEFs fostered competition in the chemical sector, and led to a substantial increase of chemical firms in most markets. During the 1950s and 1960s, the industry could accommodate such increase because demand for chemical products was growing rapidly. But, in the 1970s and 1980s, the oil shocks, the entry of competitors from the developing countries, the slower demand growth, the diminishing opportunities for product innovation made the profitability decline become a severe problem. Firms in a large number of chemical markets, especially basic intermediates, experienced excess-capacity.

As in the first post-war period, the restructuring process involved also a large number of inter-firm networks, both in production and R&D. The formation of inter-industry associations (e.g., the Association of Petrochemicals Producers in Europe) played a role in fostering such inter-firm agreements. Furthermore, mergers and acquisitions, and alliances were typically a means to reduce the number of businesses in which the chemical companies were active, and to increase the absolute size and the market share of their remaining product lines.

To sum up, during its one hundred years history, the chemical industry faced radical discontinuities, both in the technological and market-side. It is worth noting, however, that changes in networks formation were the natural answer that allowed chemical firms to survive for such a long period. If the industry faced a series of big discontinuities, it faced a long continuity in companies' life as well, and networks were probably the means by which firms adapted to radical changes.

4.2 Co-evolutionary processes: the case of environmental technologies

The heterogeneity of composition of the chemical sectoral system in terms of industry segments makes the discussion about co-evolutionary processes peculiar. Although the different elements of the sectoral system – demand, agents, technology, learning processes, markets, and institutions – are closely connected in chemicals, and their change over time often results in processes of co-evolution, these processes have not the same very nature in all different segments of the industry and, even more important, it might be hard to identify an unique co-evolutionary process for the industry as a whole.

For instance, a clear example of co-evolution of markets, institutions, agents and new agents coming into play can be found in the case of chemical processing technologies in developing countries. Since the second post-war period, developing countries have been a constantly increasing demander of process technologies in order to satisfy the needs of internal chemical industry. Demand of process technologies was mostly directed to the production of new fertilisers for the agricultural sector, and to provide an effective utilisation of large oil resources available in many developing countries. On the other hand, chemical companies from developed countries were interested in enlarging their final market by expanding in emerging countries. In this situation, local governments often came into play, opening local barriers to foreign firms, but asking them to provide processing technologies to local chemical companies. As a consequence, process technologies flowed from developed to developing countries, with SEFs being the main actors of this market together with large chemical companies. In sum, it was the interplay and mutual evolution of large companies and engineering firms from developed countries, with new entrants and local authorities from emerging countries, to allow both the markets for chemical products in developing countries and the market for process technologies in developed countries to grow.

However, the most interesting example of co-evolutionary process in chemicals is probably related to the environmental topic.[8] The chemical industry has often been accused of being highly responsible for pollution, and chemical firms, before others, have been highly committed to solve environmental problems. Some relevant accidents (e.g. Seveso, Bhopal) have contributed to generate a diffuse suspicion against chemical firms and the industry as a whole. Hence, one first element characterising the environmental issue in chemicals is related to the demand-side, and refers to the greater attention paid by consumers to pollution and environmental problems. Consumers' behaviour in this sense often resulted in the rise of new markets for environmentally-safe, less pollutant products, which have grown with some differences in terms of intensity in all developed countries.

At the same time, a second element entering into play has been government interventions. Governments have paid greater attention to pollution, and have subsequently tried to impose regulations and define appropriate control measure, in order to reduce waste production and pollution. Legislative instruments, particularly "command and control" laws, have become an important constraint for manufacturers. In general terms, government intervention can be based on two distinct instruments: i) the "command and control" approach, based on direct regulation; ii) the use of economic instruments and voluntary programmes. The first solution is characterised by a reduced flexibility, because it consists of measures aimed at directly influencing the environmental behaviour of social actors. Indeed, it determines limits, restrictions and rules related to specific product and processes. On the contrary, the second solution is comparatively more flexible, because it consists of instruments such as taxes, tradable quotas, subsidies, covenants and so on.

The interaction of these two forces, public opinion and consumers' demand, on the one hand, and government regulation, on the other hand, has had direct consequences on firms' behaviour and the creation of new markets. Indeed, chemical companies have increasingly developed and adopted new production technologies (environmental technologies, green

[8] The discussion on this topic is based on Arduini and Cesaroni (2001).

processes), and new products (e.g., less polluting solvents and paints). The first reaction to these two pressures was the development and adoption of *end-of-pipe* and *recycling* technologies. End-of-pipe technologies are purification and treatment plants which do not modify the production techniques, but are placed at the end of production processes with the aim of transforming wastes in less polluting or not injurious compounds. Recycling technologies aim at recovering, and transforming wastes so that it might be possible to re-use them. In recent days, chemical companies are increasingly substituting end-of-pipe intervention with *clean technologies*. Because they aim at preventing waste and pollution production, at reducing resource input and the use of energy, and at using recycled material, clean technologies usually demand a partial or radical modification of the process, so that pollution is avoided at the source or is reduced thanks to the recovery and valorisation of wastes. The redefinition of the chemical process often induces higher efficiency levels, so that the adoption of clean technologies induces increases in production efficiency and firms productivity.

Against this general background, some interesting differences emerge (also related to different aspects of sectoral systems of innovation and production). As shown in previous studies (Arduini and Cesaroni, 2001), differences can be found in terms of countries. For instance, German and US chemical firms show a higher innovative rate in (end-of-pipe and recycling) environmental technologies. Indeed, these two countries face different public pressures and have adopted different government regulations, compared to other countries. As a matter of fact, the United States have faced environmental problems through very strict standards, and Germany has adopted the most rigid standards of Europe. Moreover, public opinion have played an important role in influencing the environmental policy and behaviour of firms in both countries. Hence, it seems that rigid environmental standards and strong public pressure have a positive influence on the environmental innovative rate of chemical firms. Furthermore, by looking at patent statistics, it emerges that the US have a greater innovative rate in the recycling technologies than Europe, while Europe is more oriented towards end-of-pipe technologies. Europe has a grater innovative rate in the recycling field only by considering US patents. This situation suggests that a larger market for such technologies does exist in the US, while European environmental innovative activities are still devoted to the development of ex-post (end-of-pipe or recycling) solutions.

A second consequence of the growing attention to environmental issues, has been the birth of an intermediate market for environmental technologies and engineering services related to environmental technologies (the so-called *Green Industry*). The green industry began developing at the beginning of the 1970s within those countries that introduced environmental legislation and policies. The environmental regulation has been the main factor of development in this industry, and those countries with the strictest regulations are now more competitive in this sector and have larger markets. The supply-side of this industry includes environmental equipments, environmental services, and integrated environmental technologies in industrial processes and cleaner products. The sector is operated by a large number of independent, and probably small firms, specialised in the supply of environmental services and products. So, similarly to the birth of SEFs providing process technologies in chemicals, new environmentally-related SEFs have started to operate (especially in the US), thus inducing a division of labour in the environmental innovative activities.

In sum, the example of the environmental technologies seems to show a clear process of co-evolution. Demand and consumers' behaviour, and government intervention represented a clear incentive for chemical firms to develop and adopt environmentally-safe technologies and to sell green products. The complexity of technical solutions required to implement clean technologies, together with the increasing size of the green market, required the intervention of new agents, specialised in providing technological solutions and know-how. As a consequence, two new markets have emerged, one for environmentally-safe products, and the other for environmentally-safe technologies.

5. Knowledge base and learning processes: knowledge generation

The discussion carried out in the previous sections has highlighted that one of the main characteristics of the chemical sectoral system, compared to other sectors, is the process of knowledge creation and diffusion. The competitive position of firms, the organisation of the industry, and the linkages between companies and different institutions (e.g., universities) are all influenced by the possibility of generating, transferring and using new sources of knowledge. Hence, this and the following section will focus on knowledge, but differentiate between the processes of knowledge development and knowledge diffusion. In so doing, they will take into account the different organisational solutions that chemical firms adopt in the two phases. This section is about the exploration of new technologies.[9]

During the past decades different modes of managing innovative processes have emerged. Particularly, innovation is no longer an activity conducted exclusively inside the organisational structures of large corporations. The empirical evidence suggests that technological work and innovations are increasingly the outcome of interactions, formal and informal alliances among agents belonging to different economic organisations or institutions.

This section explores research collaborations that lead to patented inventions in the chemical industry, and address the issue of whether geographical proximity matters for establishing collaborations among inventors compared to the affiliation to the same firm. It is so possible to compare *geographical proximity* with *organisational proximity*.

Geographical proximity can be viewed as the fact that inventors are co-localised in the same region, while organisational proximity the fact that inventors belong to the same company.[10] By comparing geographical proximity as alternative to the organisational proximity for fostering R&D collaborations and for producing patents with certain characteristics, it is possible to compare the effectiveness of two organisation modes in performing different types of research activities: i.e. research that leads to general *vs.* more specific innovations, or research activity that involve sizeable vs. small networks of researchers.

Explicitly, we wanted to explore two propositions:

1. *Organisational proximity* (i.e. the firm) is an efficient mechanism for organising research collaborations. We expect that the effectiveness of the organisation in fostering collaborations is greater than the benefits arising from *geographical proximity*.
2. As for *geographical proximity* as a means for fostering collaboration among inventors, we expect that *geographical proximity* is a good coordination mechanism when the inventors are localised in a technology intensive region – i.e. in a technological cluster. We then expect companies to produce more complex patents in a technological cluster than in non-cluster areas.

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[9] The discussion reported in this section is based on Mariani (2000).

[10] The term "region" in this analysis can be defined either by using NUTS2 or NUTS3 codes.

By using the patent information we defined three patent characteristics:

a) *Co-localised* and *De-localised patents* (hereafter CL or DL). The address of the inventors listed in each patent is assumed to be the actual location of the innovative activity, at least for that inventor. At the country level, a patent is termed CL if all the inventors are localised in the same nation. If one or more inventors have a different nationality, the patent is defined as DL. At the regional level, a patent is CL if all the inventors are localised in the same NUTS2 region. By contrast, if at least one of them is localised in a different NUTS2 region, the patent is DL. We consider the inventors that produce a DL patent as inventors affiliated to the same company.[11]
b) *Interdisciplinary of patents*. The interdisciplinarity of a patent can be proxied by the number of supplementary classes in which the patent has been classified by the experts of the EPO. Each patent is classified in one main obligatory technological class according to the International Patent Classification (IPC). Apart from the principal IPC class, the patent officers can assign other supplementary IPC classes, if they believe that the patent falls into other technological classes as well. The higher is the number of these supplementary classes, the more the patent is interdisciplinary and "general".
c) *Breadth of the network*. The breadth of the network of inventors is proxied by the number of inventors listed in the patents. We use the interdisciplinarity of a patent and the breadth of the network that developed the patent as indicators of the "quality" of the collaboration. Intuitively, a higher coordination effort is needed when more interdisciplinary patents are developed, and when more inventors are involved.

As a first look at the data, we explored some features of a population of 97,839 chemical patents granted by the European Patent Office in 1986-1997 that have been classified in one of the following 5 chemical sectors: biotechnology, pharmaceuticals, materials, organic chemistry, polymers. While there are few patents with multiple assignees (6.8%), there is a great deal of collaboration among individuals (inventors). Only 18.3% of all chemical patents are developed by single inventors. The rest (81.7%) are invented by two or more inventors. To a larger extent than the networks of assignees, however, these networks are mostly national. Overall, 90.8% of the patents developed by multiple inventors are among individuals from the same country. Only 9.2% of patents with multiple inventors involve international linkages.

By using this framework and the information collected in patent statistics, we tried to answer the question of whether the characteristics of the firm that produced the patent or the characteristics of the region in which the inventors are located affect the collaborations and the features of resulting innovations. Specifically, we assessed whether inventors belonging to large multinational firms or located in a technological cluster have a higher probability to collaborate, to produce co-localised *vs.* de-localised patents, and to develop larger networks for more interdisciplinary innovations. Put differently, we wanted to ask whether the firm or the cluster is a better coordination mode for promoting collaborations among inventors.

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[11] The logic behind this assumption is the following. Suppose that a patent is CL. A CL patent can be thought of as the outcome of the geographical proximity among the inventors. These are either inventors belonging to the same laboratory – and hence to the same firm – or inventors belonging to different firms, and located in the same region – i.e. the cluster. Hence, a CL patent can be the outcome of the coordination played either by the firm or by the cluster. No distinction can be made by using the information that we have. By contrast, a DL patent is the result of the collaboration among inventors localised in different places. This means that the production of a DL patent is not the outcome of the geographical proximity among inventors. Since almost all DL patents are assigned to single assignees, one can assume that the inventors of a DL patent belong to the same firm. In this sense, the invention is the outcome of the *organisational proximity* as a means to reduce the cost of coordinating research networks.

5.1 The firm as a co-ordination mode for invention.

The analysis has been conducted by using a sample of 4,650 patents selected from about 10,000 chemical patents described in Appendix 1. In order to better investigate the European dimension, patents were selected when at least one inventor is localised in Europe. Their composition is as follows: 159 are Public institutions, excluding universities; 44 are universities; 133 are individual inventors (i.e. assignees who do not belong to any firm); 2,123 are large firms belonging to the Fortune 500 list (and hence labelled as "Fortune 500" firms). The remaining 2,191 firms are not listed in Fortune 500, and have been labelled as "other" firms.

One first way to look at whether *organisational proximity* is a better mechanism for fostering research collaborations compared to the *geographical proximity* among inventors, is to compute the share of DL patents over the total number of patents in the sample. About 38% of total patents are DL at the regional level. This share is 13.6% when one considers de-localised or co-localised inventors at the country level. Correspondingly, the share of CL patents at the regional level is 62% (17% of which are invented by single inventors), and it is 86.4% at the national level (16.9% are from single inventors). The higher share of CL compared to DL patents is suggestive of the fact that the *geographical proximity* among inventors might play a role in pulling them together. Unfortunately, we cannot distinguish whether this proximity is either among inventors belonging to the same firm or among inventors located in the same small geographical area. In the case of CL patents, the effect of the firm and the cluster are blended together.

However, it is possible to test the first proposition by comparing the characteristics of DL and CL patents. Specifically, we computed the mean number of inventors and the mean number of supplementary classes of CL patents, and the differences between these means and those in DL patents. These means have been used as proxies for "quality" of the coordination activity played by firms (in the case of DL patents), and by geographical proximity (in the case of CL patents).

Table 1: Characteristics of DL and CL patents.

	Share of DL patents over the total number of patents in the sample	*Number of inventors: Mean and differences between means*	*Number of supplementary classes: Mean and differences between means*
DL patents	1,767 (38%)	4.1 (0.04)	2.1 (0.05)
CL patents	2,883 (62%)	-1.4 (0.05)	-0.3 (0.06)
Mean of the total sample	4,650 (100%)	3.2 (0.03)	2.0 (0.03)

Source: Elaboration from the European Patent Office, 1998
Note: Standard Errors in parenthesis

Table 1 shows that the networks of inventors that produce DL patents, and the interdisciplinarity of these innovations are, on average, greater than those for the whole sample (and, clearly, for CL patents). This suggests that the coordination played by the *organisational proximity* is more effective than the coordination played by the *geographical proximity* among inventors. The low share of DL patents in the sample, however, suggests that the vast majority of companies do not have internally the competencies to coordinate such collaborations across distances.

After looking at the characteristics of DL and CL patents, we checked whether large firms are better at producing DL patents. To do so we distinguished between "Fortune 500" and "other" firms. Table 2 shows that "Fortune 500" companies produce a higher percentage of DL patents than "other" firms. The share of DL patents over the total number of patents invented by "Fortune 500" firms is 41.8%, compared to 30.9% of DL patents produced by "others". Moreover, patents assigned to these large multinational companies are produced by a larger number of inventors (3.5 inventors on average) and are more interdisciplinary (2.1 supplementary classes on average) than patents produced by "other" firms, that, on average, are invented by networks composed of 2.9 inventors, and list 1.8 supplementary classes.

Table 2: Firms characteristics *vs.* patent characteristics.

	DL patents: Share over the total number of patents produced by the two types of companies	*Number of inventors: Mean and differences between means*	*Number of supplementary classes: Mean and differences between means*
"Fortune 500" firms	900 *41.8%*	3.5 (0.04)	2.1 (0.04)
"Others"	771 *30.9%*	-0.6 (0.06)	-0.3 (0.06)
Mean of the total sample	1671 38.7%	3.2 (0.03)	2.0 (0.03)

Source: Our elaboration from the EPO data.
Note: Standard Errors in parenthesis. These data do not include universities, government and "individual" inventors.

Moreover, not only do very large companies coordinate larger networks of inventors to produce more interdisciplinary patents than the "others" but, when patents invented by the "Fortune 500" companies are DL, the networks of inventors becomes even larger. The average number of inventors listed in DL patents produced by "Fortune 500" companies is 4.3. The number of supplementary classes is 2.2 (not shown here). This suggests that the *organisational proximity* in large multinational companies is more effective than in smaller firms. The former can draw on globally dispersed competencies and coordinate inventors across distances to produce interdisciplinary patents.

To sum up, the fact that also "Fortune 500" companies develop more CL patents compared to DL patents suggests that *geographical proximity* matters even for large multinational firms. They develop innovations in specific regions or subsidiaries, pulling together competencies locally, at the regional level. But, the greater share of DL patents for "Fortune 500" companies compared to "other" firms, and the higher average number of inventors and supplementary classes listed in their patents suggest that large internationalised companies may also act as global networks for the development of innovations. They can coordinate inventors localised in different places. Moreover, when this happens, the coordination played by the *organisational proximity* among inventors is more effective than the *geographical proximity*, as shown by the larger networks of inventors that take part in the project and by the greater interdisciplinarity of the innovations.

5.2 The geographical cluster as a co-ordination mode for invention.

This section explores our second proposition. It examines whether the technological characteristics of the regions in which the inventors are located affect the probability that the inventors collaborate, and the characteristics of the outcome patents. Our expectation is that geographical proximity in technology-intensive regions give rise to more interdisciplinary patents and to larger networks of inventors compared to non cluster regions. The underlining argument is that in technology-intensive regions, where innovative activities agglomerate, it is easier to find the specialised and complementary competencies needed in complex R&D projects. Moreover, since people with complementary expertise are located very close to one another, the probability to collaborate increases. We also expect this probability to be higher for smaller and less global firms. These firms might use the advantages of the technological cluster to compensate the lack of internal scientific competencies and coordination capabilities.

Firstly, it is important to define a technological cluster. After looking at the distribution of different variables across the European regions we decided that the number of chemical laboratories – both private and public – was a good proxy for the technological intensity and infrastructure developed by a region in the chemical sector. As expected, other variables, such as the number of patents invented in each area, are correlated with the number of laboratories. Furthermore, we checked that firms in our database do not determine themselves the characteristics of the cluster. Indeed, these companies have only a small fraction of total R&D laboratories in each region (not shown here). We then defined a cluster according to the number of laboratories established in each region.[12]

Table 3 shows that the probability of a patent being CL in the technological clusters is higher than in non-cluster regions. The probability of CL patents goes from 49.4% in non-cluster areas to 66.0% in the "clusters". The share of DL patents falls correspondingly.

Table 3: Cluster vs. non-cluster regions and patent characteristics

	CL patents: Share over the total number of patents produced in the two types of regions	*Number of inventors: Mean and differences between means*	*Number of supplementary classes: Mean and differences between means*
Cluster regions	1,816 *66.1%*	3.3 (0.05)	1.9 (0.05)
Non-cluster regions	578 *48.3%*	-0.2 (0.06)	0.1 (0.06)
Mean of the total sample	3,944 60.7%	3.2 (0.03)	2.0 (0.03)

Source: Our elaboration from the EPO data.
Note: Standard Errors in parenthesis. These data do not include universities, government and "individual" inventors. The number of observations is 3,944.

Table 3 also shows the mean number of inventors and the mean number of supplementary classes of patents invented in cluster and non-cluster regions. The results, however, are inconclusive, suggesting that being in a cluster does not influence the level of interdisciplinarity of a patent and the breadth of the network of inventors. This might be due to the fact that the table does not highlight the net effect of being in a cluster over the interdisciplinarity and the breadth of the collaboration. To do so one needs to control for other factors.

[12] The criterion for deciding the threshold between cluster and non-cluster areas is the following. The distribution of chemical laboratories in the European regions is very skewed. Our 4,650 patents have been invented in 108 European regions. The number of chemical laboratories localised in these regions ranges from 0 to 647. Since the database on R&D labs in Europe does not provide information on the number of labs in Switzerland, Finland and Sweden, the regions from these countries are excluded from the analysis. We then have 91 regions in which 4,276 patents have been invented, and for which there are information on the number of laboratories that they host. Interestingly, however, 67 out of 91 regions host less than 100 laboratories. Only the last quartile of the European regions in our sample has between 100 and 647 chemical laboratories. We termed the regions in this quartile as the technological clusters.

The second proposition also argues that geographical proximity in the cluster is a better coordination mechanism for inducing research collaborations when firms do not have the organisation capabilities and the scientific competencies needed to develop complex R&D projects internally. Table 4 shows the percentage of patents performed in cluster and non cluster regions by "other" companies over the total number of patents performed in the two types of regions.

Table 4: Technological clusters, firms' and patents' characteristics.

	Share of patents produced by "Fortune 500"firms in the clusters and no-clusters	*Share of patents produced by the "Other" firms in the clusters and no-clusters*	*"Others" Number of inventors: Mean and differences between means*	*"Others" Number of supplementary classes: Mean and differences between means*
Cluster	1,374 *50.0%*	1,373 *50.0%*	3.0 (0.07)	1.8 (0.08)
Non-cluster	694 *58.0%*	503 *42.0%*	-0.2 (0.08)	0.1 (0.09)

Source: Our elaboration from the EPO data.
Note: Standard Errors in parenthesis. This is the total number of patents in cluster and non-cluster regions respectively. The data do not include universities, government and "individual" inventors. The number of observations is 3,944.

The probability of a patent being produced by "others" increases from 42.0% in non-cluster areas to 50.0% in the clusters. Symmetrically, the probability of a patent being produced by "Fortune 500" firms decreases from 58.0% in non-cluster areas to 50.0% in the clusters. This data supports the idea that technological clusters are comparatively more attractive for smaller and less global firms compared to large MNEs. This suggests that "Fortune 500" firms are good mechanisms to coordinate competencies and researchers localised in different firms' units and geographical areas, and that being in a technological cluster might be comparatively more beneficial for pulling together localised competencies for smaller firms than for the larger ones. Again, however, when we compute the average number of inventors and the average number of supplementary classes listed in the patents invented by "other" firms in the clusters, and compare them to those invented in the non-cluster regions, the results are inconclusive. The networks of inventors are slightly smaller in the non-cluster areas. The interdisciplinarity of the patents is slightly lower for patents invented in the clusters.

6. Knowledge base and learning processes: patterns of technology diffusion

6.1 Separability and transferability as factors fostering the transactions of technologies

Technology transfer and diffusion in the chemical industry is mainly promoted by means of market-based interactions, which give rise to a wide market for technologies (especially for process technologies). The presence and functioning of this market is based on two main conditions:

a) the knowledge base from which innovations are developed, which is generic to several applications, and can abstract from specific contexts;
b) the existence of self-reinforcing characteristics of the market for technology in chemicals.

As far as the characteristics of the **knowledge base** are concerned, the developments in the scientific understanding in many chemical disciplines and the progress in the instrumentation have caused chemical research to move away from trial-and-error procedures to science-based approaches to industrial research. Scientific discoveries and general principles are the bases to "design" new products and processes.

In general terms, the more general and abstract is a piece of knowledge, not linked to the people and organisations that develop it, the easier it is to transfer that knowledge to other people and organisations that might use it for different purposes. By contrast, as the context and firm specificity of knowledge increases, the more it is difficult and costly to transfer that knowledge (Arora and Gambardella, 1994). In turn, the possibility of transferring general and abstract knowledge allows for a division of labour in innovation, with some firms or institutions developing more general technologies and others using them for specific applications. This opens up different alternative modes for organising the innovative process, and allows firms to pursue different strategies to get access to new technologies, from in-house development to "outsourcing".

As for the chemical sector, the concept of unit operation, the emergence of chemical engineering, the growing importance of petrochemicals, and the increase in the scale and complexity of chemical plants led to the rise of a new market for engineering and process design services for chemical plants. In particular, the development of chemical engineering as an academic discipline made it easier to separate the process design from the details of the compound being produced in the plants. In turn, the codification of process technologies and the rise of specialised technology suppliers led to a vertical division of labour in the chemical-processing sector. Process technology was made into a "commodity" that could be traded due to general-purpose nature of the knowledge exchanged. Put differently, a market for process technology developed because the technology traded was nothing else than general and abstract knowledge that could be applied to different applications and markets.

This market for technological knowledge in the chemical sector was operated by a large number of small specialised and technology-based firms, the SEFs, which has been an original and persistent feature of the American chemical industry. With a few exceptions, the SEFs did not develop radically new processes. They were good at moving down the learning curve for processes invented by the large oil and chemical companies. And, equally important, they acted as independent licensors on behalf of other firms' technology.

It is also worth noting that the SEFs started as an American phenomenon.[13] This was because the large size of the market has been a crucial factor for the rise of SEFs (Freeman, 1968). By the end of World War II, the world demand of chemical products grew – especially of petrochemicals – and pushed companies to raise the scale of production. The large scale increased the size and complexity of the plants, so that companies often faced a technological capability constraint, and demanded the intervention of external engineering specialists.

Finally, the existence of the SEFs, whose business is to sell process technologies and to appropriate rents from innovations, encouraged other chemical and oil firms to license their own technologies for making profits out of them. This closely relates to the second condition (i.e., the presence of a **self-reinforcing mechanism**) that allowed the market for technology in the chemicals to persist over time.

The traditional and managerial literature (among others, see Teece, 1988) holds that companies can gain value from their innovations mainly by exploiting them in-house. There

[13] According to Freeman (1968), 50% of the total value of engineering contracts world-wide in 1960-66 were done by American SEFs.

are many reasons why technology licensing is considered an undesirable strategy. Apart from the existence of transaction costs problems, and of cognitive constraints, the main reason is that by licensing, firms create new competitors in the downstream product market, hence reducing their profits and dissipating rents. In other words, firms incur in the *rent dissipation effect*, which consists in the erosion of profits due to another firm competing in downstream market. But licensing also provides revenues from the sale of technologies (the *revenue effect*), in the form of licensing payments. Hence, the question is under what conditions the revenue effect is greater than the rent dissipation effect, so that of inducing licensing (Arora and Fosfuri, 1999).

The answer to this question mainly depends on industry structure, and especially on the presence of a situation of monopoly or competition in the product market. In the case of the chemical sector, technology licensors that lack the downstream complementary assets in production and commercialisation sell more licenses – in this case, the rent dissipation effect is zero. However, in the presence of such licensors, downstream producers may be induced to license their technologies as well. In fact, given that the licensing activity of others create new competitors in any case, and hence reduces the capability to gain profits in the product market, the downstream producers may well have incentives in competing in the market for technologies, by selling their proprietary technologies. And this is what exactly happened in the chemical sector.

The SEFs acted as independent technology suppliers, by selling process technologies to potential entrants in the product markets, and in turn this behaviour induced downstream chemical companies to become technology suppliers as well. Moreover, licensing by rivals in the downstream markets increased the propensity of other chemical companies to license their proprietary technologies as well. In this sense, licensing strategies tend to strengthen over time (i.e., there are self-reinforcing mechanisms). As a matter of fact, once established, the market for technology tends to persist over time. Indeed, in the chemical sector the market for process technologies has been a constant feature over the last forty years. Even today, Arora and Fosfuri (2000), using data on worlwide technology licensing during the 1980s, find that homogeneous sectors like air separation, pulp and paper, and petrochemicals are characterised by extensive licensing. On the contrary, in differentiated product groups like organic chemicals, licensing is quite limited. Furthermore, they find that in those sub-sectors where firms without downstream assets license more, large chemical producers themselves tend to license more.

6.2 Evidence on the existence of markets for technological knowledge

The existence of a market for process technologies, the role of SEFs, and the behaviour of large chemical companies has already been introduced in the previous discussion. In this section we will try to describe this market in greater detail, both by comparing different means for transferring technological knowledge in chemicals, and by taking into consideration country characteristics.[14]

By using information from the *Chem-Intell* database, we firstly looked at the country distribution of the licensors of 5,442 licensing agreements that were signed in the US, Europe,

[14] An extensive analysis on this issue can be found in Cesaroni and Mariani (2001).

Japan and Germany.[15] We were able to distinguish between four kinds of technology suppliers:

a) *top chemical companies* – those ranking in the top 50 positions in terms of number of plants owned and reported in the dataset;
b) *other chemical companies* – those owning more than 5 plants, but not top companies;
c) *SEFs*;
d) *staff* – the case in which firms developed internally their process technologies.

Table 5: Licensing agreements: 1980-1997 (Shares of Total Licenses by Type of Licensor and Region)

	Receiving Country				
Licensor	Germany	UK	Japan	US	Total
Top Chem. Firms	1.7	1.4	2.7	3.7	9.5
Other Chem. Firms	0.1	0.2	0.2	0.3	0.8
SEFs	8.9	8.3	10.4	23.3	50.9
Staff	7.4	5.6	9.5	16.3	38.8
Total	18.1	15.5	22.8	43.6	100.00

Source: Chem-Intell, 1998.

Table 5 shows that SEFs are the most important source of chemical processes technologies in all the developed countries. They own 50.9% of the total market for technology. Half of the transactions are in the US (23.3%), followed by in-house technology development (16.3%). However, when one considers the frequencies of SEFs transactions and in-house technology development conditional upon each receiving country, these shares are very similar. In all the four countries, about 50% of technologies are supplied by SEFs, and 40% by companies' staff. This suggests that, apart from using its own technology expertise, chemical companies often rely on the specialised suppliers of process technologies. In order to analyse the phenomenon in greater detail, table 6 looks at the type of companies involved in the vertical linkages.

Table 6: Licensing agreements: 1980-1997 (Shares of Total Licenses by Type of Licensor and Licensee)

	Receiving Company			
Licensor	Top Chem. Firms	Other Chem. Firms	"Non" Chem. Firms *	Total
Top Chem. Firms	1.6	6.9	2.7	11.2
Other Chem. Firms	0.2	0.9	0.4	1.5
SEFs	9.3	39.8	19.1	68.2
Staff	8.6	8.8	1.7	19.1
Total	19.7	56.4	23.9	100.00

* *"Non" Chemical Companies*: Companies with 5 or less than 5 plants.
Source: Chem-Intell, 1998.

Table 6 confirms that SEFs are the main suppliers of technologies in the chemical sector – they cover the 68.2% of the total market for licensing. This is true for all types of companies with at least one plant. The SEFs license almost 50% of the technologies used by the top chemical firms, 70% of the know-how used by the companies with at least 5 chemical plants, and 80% of the technology used by the companies with less than 5 plants. Top chemical companies have the lowest share of technology received from the SEFs, probably due to their higher technological capabilities developed in-house. This is confirmed by table 6. Not only

[15] The *Chem-Intell* database collects information on 36,343 plants built world-wide since 1980. For each plant, a number of detailed information are present: kind of production realised, production capacity, technology used, owner of the plant, contractor which provided the engineering services, licensor, construction year, and so on. It is so possible to identify the existence of repetitive patterns between different agents (chemical companies and specialised suppliers) and to test the existence of the degree of persistence.

top chemical companies develop by themselves almost half of their technological know-how, but they also sell these technologies to other chemical companies.

The role of SEFs in licensing is further analysed in table 7. Although the SEFs started as an American phenomenon, table 7 shows that other countries are now successfully competing with the US in this field, particularly in Europe and the third-world markets. However, while the US SEFs have a sizable share of the European market, the European SEFs have only a small share of the US market.

Table 7: Market share of SEFs – Licenses: 1980-1990 (Shares of Total Number of Plants by Region).

	Regions				
Nationality of SEFs	USA	West Europe	Japan	Rest of the World	Share of Total World Market
USA	18.0	10.3	6.5	16.9	15.1
West Germany	3.1	11.3	1.0	10.2	8.8
UK	1.2	3.0	2.7	1.4	2.4
Italy	0.1	1.4	0.0	2.2	1.6
France	0.1	0.6	0.0	0.9	0.7
Japan	0.1	0.1	1.5	1.1	0.7

Source: Chemical Age Profile (Arora and Gambardella, 1998).

In particular, table 7 shows that the market share of US SEFs in licensing is about 15%, followed by West Germany with a share of 8.8%. However, if one looks at the share of US licenses in Europe and Japan with respect to the correspondent shares of her competitors, the comparative advantage of US SEFs in licensing is even more apparent.

Finally, by using information drawn from the *SDC* database, we tried to estimate the "value" of the licensing market in chemicals during the period 1990-1997.[16] Results are reported on table 8.

Table 8: Licenses: value and number by sector: 1990-1997 (Millions of dollars)

	Estimated Value per License	**Nr. of Licenses**	**Total Value per Sector**
General Chemicals	104.2	248	25,835.4
Pharmaceuticals	117.4	1,394	163,606.7
Soaps & Cosmetics	3.0	29	87.0
Rubber & Plastics	3.0	41	123.0
Petroleum Refining	6.2	33	203.2
Average	46.7	349	16,298.3

Source: SDC, 1998.

In order to calculate the values, we proceeded as follows. We first considered the whole SDC database (52,000 transactions), and selected the licensing agreements that disclosed the unit value. We then attributed each license to one of the 5 industrial sectors shown in table 8. For each of these 5 sectors we computed the average value of a license (first column on the left).[17] We then calculated the number of licenses by sector and, based on the estimated mean value

[16] The SDC database (*Securities Data Company*, 1998) and *Chem-Intell* (1998). The SDC database typically reports product licenses. The database is constructed from SEC filings (10-Qs), financial journals, news wire services, proxies and quarterly reports. There are information on about 52,000 inter-firm agreements world-wide in all sectors. For each transaction there are information on the type of agreement (i.e. license, joint R&D, joint manufacturing, etc.), whether the agreement involves a technology transfer, the number of partners involved, the sector, the country and the region of the transaction. Data are available from 1990 to 1997.

[17] In two cases – i.e. soap and cosmetics, and rubber and plastics – we had to few observations (less than 5 licenses). Instead of calculating the mean value, we considered the median value of the whole sample of alliances.

per license, we computed the total amount of money involved in the exchange of knowledge in the 5 sectors (first column on the right).

Table 8 shows that the pharmaceutical sector reports the highest number of licensing agreements and the highest value per alliance, and hence moves the largest amount of money. By contrast, in the general chemical sector, licensing agreements tend to be less numerous, although the unit value is rather high. The market for knowledge seems to be less developed in soaps and cosmetics, rubber and plastics and petroleum refining, where both the number and the unit value of agreements are low compared to the other sectors in table 8.

6.3 Licensing strategies by large companies

There are quite a few examples in the chemical industry showing that firms increasingly choose to license their technologies. Companies such as Union Carbide, Amoco, Montedison, Phillips, Exxon and British Petroleum have been important technology suppliers. Also some leading chemical producers such as Dow Chemical, DuPont, Monsanto and Hoechst, traditionally reluctant to license, recently started to sell proprietary technologies. This section analyses technology strategies of the 40 largest corporations from Western Europe, North America and Japan.[18] We selected from *Chem-Intell* all the plants in which these 40 companies appeared as technology licensors. Figure 1 shows the name of the companies, and the share of technologies that they exploit in-house (*Staff*) or license out to other firms (*Licens*).

Figure 1 shows that large corporations license a large amount of their proprietary processing technologies. On average, 52.5% of internally developed technologies are sold to other firms. However, differences emerge among companies. Firms such as Air Liquide, Mitsubishi and Texaco license more than 80% of their proprietary technologies. On the other extreme, Nestle sells only a small share of its technologies, and Grupo Torras and Enterprises des Recherchers exploit their technologies only internally.

This suggests that firms adopt different technological strategies. For example, Exxon and Union Carbide have the same number of technologies, but show different strategies toward licensing. Union Carbide licenses about 70% of process technologies, while Exxon uses the same share of technologies for internal production purposes.

Interestingly, Figure 1 also shows that there is a high share of technologies (20.4%) that firms both exploit in-house and license out to other firms. In so doing they license process technologies to potential competitors, thus reducing expected profits in the product market.[19] Also in this case, there are differences among firms. For example, companies like Allied Signal, Enterprises de Recherches and Nestle do not have technologies that are both licensed and used internally. Others, such as BOC and Solvay, use for both internal and external purposes about 50% of their technologies.

The question is then: why should (chemical) companies license their technologies to other companies in the same market? What are the specific features of the chemical industry that made licensing by large companies so diffused? In general terms (and for sectors also different from chemicals), Arora, Fosfuri and Gambardella (2000) suggest that the decision on whether licensing or exploiting the technology in-house depends on three main factors. First,

[18] Firm size is measured by the total number of plants as reported by *Chem-Intell*.

[19] One should take into account the geographical localisation of the licensee, and the possibility that the markets of the licensor and the licensee are geographically different. In this case, the companies would not compete in the same market.

if the firm has distinctive complementary assets in production and marketing, compared to other competing firms, the efficient strategy is in-house exploitation of technology. On the contrary, licensing might become the right strategy, in order to acquire some rents from innovation. Second, the decision also depends on the nature and importance of the transaction costs involved in the exchange of complementary assets, compared with the importance of transaction costs involved in selling or licensing the technology. If the latter are greater than the former, a company without the needed complementary assets may choose to acquire those assets in the specialised market, and then exploit the technology in-house. This strategy allows firms to save resources, compared with the strategy of licensing, because of the smaller amount of transaction costs. Finally, firms may choose to license their proprietary technologies instead of exploiting them in-house, because of the extent of competition in the final product market. The degree of competition influences the capability for firms of extracting returns, so that the "best strategy" is to operate in the market (technology vs. product market) with the smaller level of competition.

However, what we claim is that what induced large chemical companies to start licensing out their process technologies were specific conditions of sectoral system described in the previous sections. Among others, characteristics of the knowledge base in chemicals, and the role and licensing activity of SEFs – acting as independent technology suppliers to potential entrants – were key in inducing large chemical companies to license out their process technologies. In other words, while technology licensing by large firms might be potentially observable in different sectors and industries, the evolution (and co-evolution) of all elements of the chemical sectoral system made this potentiality become feasible in chemicals. In this sense, the sectoral dimension implicit in the Sectoral System approach is clearly relevant.

7. Conclusions

The objective of this study was to assess the different dimensions of the chemical sectoral system. In some respect, chemicals provide an excellent basis for analysing this issue. In the first place, this is a very important and innovative industry in all advanced countries, and worldwide as well. Second, this is an industry whose almost 200 years history provides an opportunity to examine the evolution and co-evolution processes that involved single agents (both inventors, firms and research institutes), the relationships among agents, and the industry as a whole. Third, being the chemical industry a science-based industry, it gives the opportunity to explore in depth the processes of technology creation and diffusion, and the role of knowledge in shaping companies performances and industry organisation.

Indeed, the history of the industry can be characterised by the presence of a series of big *discontinuities*. The dyestuff model, the development of polymer chemistry (i.e., the science of chemical products), and the chemical engineering (i.e., the science of chemical processes) were major changes in the knowledge sphere. The shift from coal to petrochemicals in the years before the Second World War had strong consequences on regional leadership in chemicals, and allowed the American chemical industry to catch up with Europe. The emergence of specialised engineering firms (SEFs) made it easier the outsourcing of process technologies and allowed a growing division of labour at the industry level between SEFs and chemical companies. The world demand decrease during the 1980s induced a process of industry restructuring.

However, the history of the chemical industry is also characterised by a big *continuity* in companies' life, which were able to evolve and compete over time. BASF, Bayer, Hoechst, ICI, Agfa, ICI, i.e. some of the leading chemical companies nowadays, have more than one hundred years history and have been top chemical producers during all this period. This means that between small and large companies, markets, research institutions and other organisations there has been a process of *co-evolution*, with firms playing the central role within the chemical system.

It is possible to explore some of the relevant trends of this system:

- the more and more frequent linkages between firms and universities;
- the increasing role of networks;
- the increasing division of labour at the industry level between chemical companies and technology suppliers;
- the increasing relationships with users, in order to better specify products characteristics;
- the increasing role of knowledge and R&D as a source of competitive advantages and growth.

Among these dimensions, this study explored especially the role of knowledge, by focusing on the mechanisms for knowledge generations and for knowledge (technology) diffusion. As far as knowledge generation is concerned, we compared the firm and the technological cluster as organisational modes for producing innovations. In this respect, the results confirm a major role for large firms. Indeed, the larger the firm is:

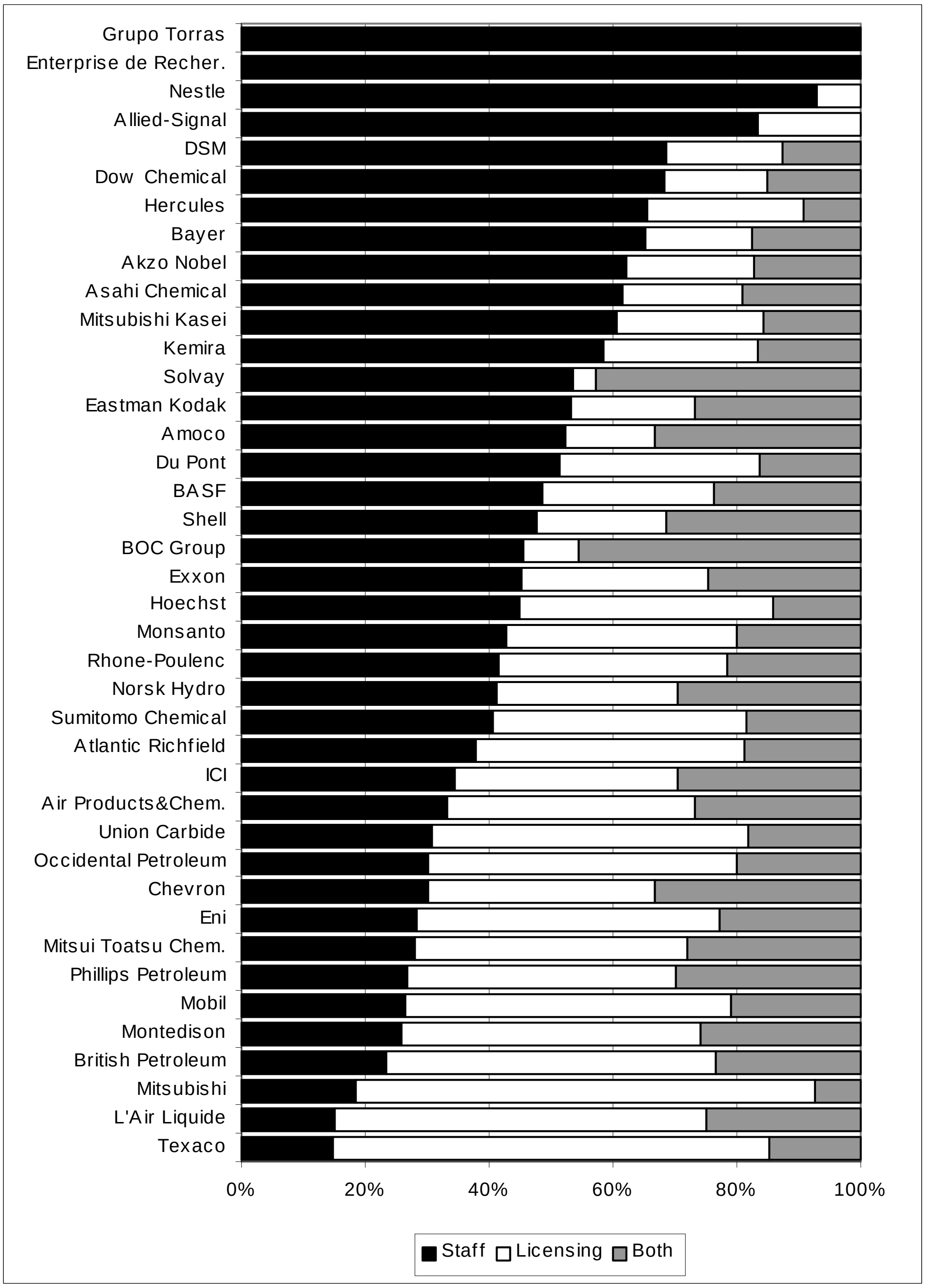
- the lower is the probability that inventors are co-localised, i.e. the innovation is developed by inventors localised in the same place;
- the largest is the network of inventors that collaborate to produce a patent;
- the higher is the number of supplementary classes listed in the patent, i.e. the higher is the interdisciplinarity of the patent.

However, for smaller companies there exists a comparative advantage of being in a technological cluster, for it typically features a good deal of different and complementary competencies inside the same territorial area. Therefore, firms localised in a technological cluster have limited need for finding these competencies outside the region. Furthermore, from a comparative viewpoint, geographical proximity in a technological intense region plays a more important coordination function for companies that lack the internal scientific competencies and the organisational capabilities needed to coordinate the R&D collaborations. In this sense, geographical proximity is a good substitute for the organisational proximity.

Once the technology has been developed, large companies play a critical role as well. Indeed, the traditional managerial literature has considered large companies as the locus where the phases of technology development and use are naturally integrated – i.e., large companies develop new technologies mainly for internal production needs. In the last years, however, large firms in chemicals have enlarged the spectrum of strategic options, and have increased their propensity to license out proprietary technologies to other firms. In so doing, they can be considered one of the main actors of that market for (process) technologies that begun with the appearance of the specialised engineering firms during the 1960s in the US.

Why in chemicals? This study clearly showed that the answer lies in the knowledge base of the sector and the process of increasing codificability and transferability that has characterised the chemical sector over the time. The advances in the chemical discipline (polymer chemistry and chemical engineering) have created the bases for a greater codificability. And firms' behaviour has enhanced the transferability of chemical technologies. As a result, however, technological knowledge has become a central feature of the chemical sectoral system, which capable of influencing firms' competitive advantages, industry structure, the relationships between different institutions, and their evolution over time.

Figure 1: Use of proprietary technologies (largest European, North American and Japanese companies)



Source: Chem-Intell, *1998*

Appendix 1. The networks of inventors: data description.

The data used in Section 3 of this paper are drawn from various sources. First, from the *European Patent Office* (EPO, 1998), we extracted a database of 201,531 chemical patents granted and applied between 1986-1997. From this universe of patents we selected a random sample of 10,000 chemical patents and classified them in 5 technological classes: biotechnology, materials, organic chemistry, pharmaceuticals and polymers. The correspondence table between IPC technological classes in these 5 classes is provided by Rossana Pammolli.

From all the information available in the front page of a patent document we collected the following details on each chemical patent: the number, names and addresses of the assignees; the number, name and addresses of the inventors; the obligatory IPC class, and the number and type of supplementary IPC classes; the date of the patent application. We did not make any distinction between patent applications that have been granted, and those that have not been granted (yet).

The first step of the preparation of the patent data was to locate the invention geographically. For the 10,000 sample patents, the address of the inventor was used to assign each inventor to a specific country. Each patent was then defined as CL or DL at the country level. The number of assignees, the number of inventors, and the number of supplementary classes were also calculated, so to define the breadth of the networks of assignees and inventors, and the level of interdisciplinary of the patents.

The second step was to consider the patents (in the 10,000 sample patents) in which at least one inventor is located in Europe. By using the information on the zip code contained in the addresses, we assigned the inventors of 4,650 patents to a specific NUTS3, NUT2, and NUT1 region, and decided whether a patent was CL or DL at the regional level. Again, the number of assignees, the number of inventors, and the number of supplementary classes were calculated.

The names of the applicants of these 10,000 patents were standardised in order to merge mother and daughter firms under the same name. The *Who Owns Whom* (1995) database was used to investigate these mother-daughter relations. *Fortune 500* (1995) was used to select the firms that we termed "Fortune 500".

We also collected information about the NUTS3 regions in which the inventors were located.[20] From the *EUROSTAT REGIO* database (1999) we collected information about the economic characteristics of these regions, such as the GDP, the population, the size of the regions, etc. We also downloaded some 9,000 chemical laboratories from the *European R&D database* (by Reed Elsevier Publisher, 1996). The laboratories were classified as private labs if they were firms' laboratories, or public labs if they were government research institutions, universities, and hospitals. They were also assigned to their specific NUTS3 regions.

[20] When the inventors were CL, the NUTS3 region where the patent was invented was obviously the region where all the inventors were located. When the inventors were DL, we considered the region where more than 50% of the inventors were located. In the few cases in which this 50% was not reached, we used the region of the first inventor listed in the patent.

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