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DIVERSIFICATION AND HYBRIDISATION IN FIRM KNOWLEDGE BASES IN NANOTECHNOLOGIES

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DIVERSIFICATION AND HYBRIDISATION IN FIRM KNOWLEDGE BASES IN NANOTECHNOLOGIES

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The paper investigates the linkages between characteristics of technologies and a firms' knowledge base. Nanotechnologies have been defined as converging technologies that operate at the nanoscale, and which require integration to fulfil their economic promises. The paper analyses the degree of convergence and the convergence mechanisms within a firm's knowledge base. If convergence predominates as it has been claimed, nanotechnologies are not competence destroyers and the development is based on the extension of the knowledge base of existing firms. Based on the worldwide database of nanofirms, the paper examines the influence of the characteristics of the technologies on the structure of the firm knowledge base. It argues that nano S&T patterns of development combine competence destroying activities and a critical role of research facilities and technological platforms. While the competence destroying characteristics of nanotechnologies give a premium to emerging companies, the role of research and production facilities strengthens large incumbent competitive position and geographically polarises the emergence of small dedicated nanofirms.

Keywords: firm knowledge base, nanotechnology, coherence, scope, science regime, converging technologies

JEL classification: O31, O32, L22,

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1. Introduction

What is the engine of the economic development of nanotechnologies? Which are the effects of nanotechnologies on the firms' knowledge? Previous researches e.g. (Darby *et al.*, 2003) suggest that the development of nanotechnologies is a *Grilichesian breakthrough* which follows a similar pattern to that of biotechnology. Based on Hill and Rothaermel (2003), the relative economic performance of incumbents has been predicted to be at risk of decline as a result of the emergence of a competence destroyer technology and successful nanotechnology-based innovations (Shea, 2005).

However, nanotechnologies borrow not only from biotechnology but also from microelectronics. Abernathy and Utterback (1978) have underlined the critical role of large incumbents like Fairchild semiconductors, IBM and Texas Instruments who were deeply involved in the early development of micro-electronics during the 60's and 70's. Microelectronics and biotechnologies followed two different evolutionary paths over recent decades.

Nanotechnology involves the manipulation and control of living and non living materials at the scale of a nanometer (one billionth of a meter). While this formal definition is straightforward, the field of nanotechnology is a rapidly evolving research domain which covers multiple scientific disciplines and technological domains. We emphasise one of the characteristics of the nanotechnologies *i.e.* the convergence of technologies from physics, engineering, molecular biology and chemistry (Nordmann, 2004). The term "nanotechnologies" defines not only the 'sum' of these different disciplines but also their convergence. Nanotech's power and economic promises will be fully realized with the integration of nanoscale technologies within nanodevices (such as chips) or in more traditional products such as nanotubes in the tyre industry (The Institute of Nanotechnology, 2005). Compared to biotechnology, however, nanotechnologies are built on the technologies that had emerged in previous waves of research and technology development, and thus actors - be they academics, firms or technology transfer organisations like incubators or start-ups - already exist, and are adapting their operations to integrate nanotechnologies and converging fields.

This paper argues that the characteristics of the technology (as competence destroyer or enhancer, divergent or convergent, etc.) influence the characteristics of the knowledge base of the firm. It focuses on the characteristics and evolution of the knowledge base of firms involved in nanotechnologies. To what extent does the involvement in nanotechnologies increase the scope and the diversity of the knowledge base? To what extent does hybridisation amongst technologies take place within firms? Do knowledge bases of large firms and small firms follow the same paths of evolution? Lessons from biotechnologies are clear. Nesta and Saviotti (Nesta *et al.*, 2005) argue that the coherence of the knowledge base contributes significantly to the firm innovative performance, while Zhang *et al*. (Zhang *et al.*, 2005) show the more intense a firm's research knowledge base is, the less likely it will be to collaborate with others (in particular with new and small firms).. That is, where a firm has a deep understanding of a particular research-field, it is less likely to collaborate with others (in particular with new and small firms). This paper analyses if **nanotechnologies are competence destroyers** (Boisot, 1995) (**as was the case in biotechnology), or rather if they enhance hybridisation amongst technologies and the existing knowledge base**. If nano science and technology ('nano S&T') are similar to biotechnology, involvement in nano S&T may increase the diversity of the knowledge base of the existing large firms and of the previous generation of start-ups (biotechnology and micro-electronics). If nanotechnologies are competence destroying, (i.e. they are a set of technologies which tend to discard previous technological developments, rather than permit accumulation of knowledge) they would tend to decrease the knowledge base coherence of these firms and give a premium to new entrants. On the contrary, if nano S&T are developed through the hybridisation based of parent technologies, large incumbents would tend to retain their competitive advantage.

The paper first discusses the influence of the characteristics of the technologies on the structure of a firm's knowledge base. It formulates hypotheses which are tested on a worldwide database of biotechnology firms (www.nanodistrict.com). It describes the scientific knowledge base through publications and the technological base of firms through patents, , as well as financial data as well as more qualitative data on the organisation of research within the firm. The paper shows that the emergence of Nano S&T modifies a firm's knowledge base. Different trajectories are explored. The hybridisation mechanisms amongst different scientific and technological subfields in the early stages of nanotechnologies are found to take place at the firm level as well as at cluster levels. Small firms appear to develop nano S&T through hybridisation more than large firms, which are agglomerating rather than hybridising different competencies.

2. Introduction to nano S&T and literature review

Nano S&T is considered as an emerging technology based on the convergence of different existing scientific fields, biotechnology, information technology and cognitive sciences (concept of Nano – Bio – Information and Cognition (NBIC) from M. Rocco (2002)). At the crossroad of different scientific and technological fields, firms may follow? several paths to develop and enrich their knowledge base.

Nanosciences and nanotechnologies (Nano S&T)

The past 5 years have seen an explosion of interest in the area of science and technology labelled “nanotechnology.” Although at an early stage, promises have lead to high expectations of the fruits that could be harvested from investment into nanotechnology development (Saxl, 2005). However, unlike previous high-technology hypes (well-founded or not), nanotechnology covers a diverse field of sciences and engineering, crosses boundaries between them and aims to utilize the very fundamental characteristics of matter by manipulation and control at the nanoscale. Much of nanoscience and many nanotechnologies involve 'top down' techniques, producing very small structures from larger pieces of material, for example by etching to create circuits on the surface of a silicon microchip. But they may also be constructed by 'bottom up' techniques, atom by atom or molecule by molecule, including develioping the ‘self-assembly’ technique, in which the atoms or molecules arrange themselves into a structure due to their natural properties.

C. Shea (2005) points to the most important events in nanoscience to date as the inventions in the late 80’s of atomic force microscopy (AFM) and scanning tunneling microscopy (STM) by IBM researchers, which have led to the ability to observe and manipulate nanoscopic phenomena and atoms. During the same period Drexler emphasized the promises of nanotechnologies and channeled public and private investment to nano S&T,[2] and the 1996 Nobel Prize award to R. Smalley’s team for the manipulation of atoms into a fabricated structure cemented nanotechnology’s reputation as a cutting edge research field.

[2] Drexler KE. 1986. The engine of Creation. MIT Press: Cambridge, Massachusetts and Drexler KE. 1988. *The coming era of Nanotechnology*. MIT Press: Cambridge, Massachusetts

The specificities of nano S&T

Just as biotechnology development benefited from Cohen and Boyer's invention of the PCR (1973), nano S&T depend on the availability of tools to enable research and production. Established firms such as IBM, with a history of producing tools to enhance research and fabrication performances, have been highly involved in nano S&T since the very beginning. Their involvement brings with it strong ties to the field of scientific advances and also to the mobilization of public support to boost investments in the new fields. While the development of biotechnology is based on the exploration of multiple competing hypotheses, nano S&T borrows from different and independent fields, and its development is based on the convergence and hybridising of different existing technologies.

Table 1 compares three different recently-developed high tech regimes: nuclear technology, biotechnology and nanotechnology. (Bonaccorsi, 2005). It underlines in each case the dynamics of the technology and its crystallization mode. The traits of each technology influence the patterns of industrial organisation, the role of public authorities and the structure of the firm knowledge base. In the nuclear technology, the dynamics depend critically on the construction of large technical systems and infrastructures. A limited number of solutions have been selected to allow cumulative improvement within a given technological trajectory. The situation in biotechnology has been completely different, with individual actors exploring different hypotheses simultaneously. A low level of equipment was required initially, even if recent years have witnessed the growing importance of instrumentation. As converging technologies, nanotechnologies are based on the convergence amongst paradigms or the hybridisation between technologies within given trajectories, which they borrow from the parent technologies (microelectronics, IT and biotechnologies). Do they follow similar patterns (such as the miniaturisation process of microelectronics) or do new technological trajectories emerge?

Table 1: Specificities of nano S&T within waves of high techs

	NUCLEAR	BIOTECHNOLOGY	NANOTECHNOLOGY
Dynamics/ crystallisation	Large objects/ technical systems	Science based industry. Competing hypothesis. Low level of infrastructure required	Hybridisation amongst previously separate scientific and technological fields
Trajectory	Dominant design cumulative improvements	Competition between paradigms	Trajectories based on parent technologies (microelectronics, materials and biotechnology).
Critical infrastructures	Specific large equipment	Generic infrastructures (IPR, internet...)	Existing research facilities which are adapted and developed.
Industrial organisation	Large firms (monopoly). Public investment	Creation of start-ups bridging academia and large firms close to the market. Relative decline of incumbents' economic performance	Large incumbents, high tech start-ups from the previous waves and new start-up co-exist.
Coordination modes	Large national programmes	Network and clusters	Regional cluster / 'science district'

In nanotechnologies, required research facilities or infrastructure may include large ultra-clean rooms, atomic force microscopes for observation and manipulation at the nanoscale, e-beam lithography and nano-imprint lithography to make the channels, pores and circuits needed for the research. The Albany Nano Tech (US) (http://www.albanynanotech.org/) houses state of the art R&D and prototype manufacturing infrastructure for nano/microelectronics, nanophotonics and optoelectronics and nano/micro systems. The Albany Nanotech website emphasises the leading role of technological platform as a key element of the strategy to foster nano S&T development. Research facilities are costly investments which require not only buildings and equipment but also skilled engineers to run specialised and complex scientific tools. For example, a state-of-the art Extreme Ultra-Violet lithography platform is reported to cost some $40 million[3] while established locations of micro(nano)electronics have involved over €5 billions of investment (Dresden, Imec, Minatec

[3] *EUV lithography takes shape at ASML*, Solid State Technology, December 2005, www.solidstate.com

and two or three other locations in Europe). At each of these locations Nano S&T has developed from the trajectories of existing local parent technologies and specialisations. (By contrast biotechnology development tended to emerge as a result of separate local start-ups, while nuclear research facilities represented concentrations assembled by national programmes.)

In addition to the requirement for infrastructures, which gives a premium to incumbents (Rothaermel *et al.*, 2005), the development of nano S&T is based on existing actors and existing clusters. The first enabling tools were developed by large incumbents, and both established micro-electronics firms and the biotechnology start-ups of the 80-90's are deeply involved in nano S&T. Thus locations with a long identification with microelectronics - like Minatec in Grenoble (see Mangematin *et al.*, 2005) - or with a biotechnology tradition - such as Cambridge (UK) or Øresund (Copenhagen/Malmö) - exemplify both the key role of the access to research facilities but also the importance of already-installed industrial and scientific bases. The nanotechnology situation combines elements of the industrial organisation of previous waves: the key role of large incumbents in investing in R&D, manufacturing nanodevices and commercialisation on the one hand and the presence of specialised science based start-ups on the other.

In contrast to the emergence of the biotechnology industry, the progress of nano S&T benefited from the fact that many science based start-ups had already been created during the biotechnology or IT waves. These factors lead to a strong agglomeration effect, although, from a public policy point of view, the picture is still different from national and international cost-sharing agreements of the "big science model". Nanotechnologies have been seen as a strategic field (Rip, 1997) from the very beginning, with firms involved in the creation and management of research facilities. Again, contrary to the development in biotechnologies, research facilities have not been created from scratch, but rather developed from extending and adapting existing facilities to fit with the new converging technologies.

Finally, the emerging modes of coordination in nano S&T are still undecided. Governments have been supporting the development of high technology through different tools. Large national programmes have been mobilized to support the emergence of the nuclear industry, national and decentralised programmes have been supporting the formation of alliances, clusters and networks in the biotechnology industry while regional authorities are mobilizing national and European resources to support the creation of "pole de competitivite" *i.e.* large regional high tech clusters.

3. Knowledge base of nanotechnology firms:

The characteristics of the knowledge in nano S&T firms throws into question the conclusions of scholars who have bases their arguments on a study of biotechnology firms, especially US biomedicals. Nesta and Saviotti (Nesta *et al.*, 2005) have shown that the coherence of a firm's knowledge base *defined as the complementarity amongst its scientific and technological competencies* can contribute significantly to its innovative performance. We explore the changing characteristics of the knowledge base of firms involved in the converging technologies of nano S&Tech.

Specialization in nano S&T and knowledge base size

IBM, Hitachi, Samsung, Lucent Technologies, Eastman Kodak, Siemens, DuPont, Infineon are amongst those firms which have filled more than 100 nano-patents during the last 10 years. The share of nano-patents and nano-publications in a firm's knowledge base can range from full specialization to a quite negligible share, and, in fact, the *degree of specialization in nano S&T* R&D activities varies considerably amongst firms. Since this degree of specialization reflects past decisions on R&D investments, we can learn about its determinants by looking at the characteristics of the knowledge base that make firms more or less reluctant to invest in a new technology.

Nesta and Saviotti (2005) and Breschi et al. (Breschi et al., 2003) state that knowledge can be efficiently accumulated and integrated only by adding related types of knowledge. They concentrate on two properties of the firm's knowledge base: its scope and its coherence. Scope relates to the diversity of a knowledge base and reflects the number of activities, of markets and of research projects implemented within a firm. The larger the scope, the higher the diversity of knowledge monitored by the firm. Coherence describes the relatedness amongst individual pieces of scientific and technological knowledge. The more related the components of knowledge, the higher the coherence of the firm's knowledge base. Theoreticians argue about the coherence of the firm, and Teece et al. (Teece et al., 1994) judge that a firm is not a collection of unrelated activities. When it diversifies to integrate a new technology or a new field, the firm seeks to benefit from economies of scope by diversifying its activities in related businesses (Morel et al., 1999; Ramanujam et al., 1989). In their study of ten major pharmaceutical firms, Henderson and Cockburn (Henderson et al., 1994) showed how different types of knowledge management practices acted as sources of idiosyncratic firm advantage, yielding architectural or integrative competencies rather than specialised and disciplinary ones.

When firms engage in a new activity, the effects on the structure of the knowledge base depend upon the characteristics of the emerging technology. In a *competence destroying* regime like biotechnology, the involvement in research in such an area increases the heterogeneity of the knowledge base. It corresponds to the addition of a new field which is unconnected with the existing knowledge base. The enlargement of the scope of the knowledge base leads to the reduction of its coherence. In other words, the integration of knowledge across different disciplines and the expansion of the original knowledge base over the ancient boundaries imply that firms have to explore new competencies at the edge of their knowledge. The new emerging technology is added in *juxtaposition* to existing ones. Scientists have predicted that the reduction of the coherence of the knowledge may shrink the innovative performance of the firm (Hill and Rothaermel, 2002). As a consequence, firms with large knowledge bases will be reluctant to invest directly in competence destroying activities. They prefer allying with specialized firms to explore competence destroying activities as they try not to juxtapose too many fields within their internal knowledge base.

When technologies are built through *hybridization* with existing technologies within the firm knowledge base, firms with large knowledge bases have strong incentives to invest in the new technology. The technological developments are based on the competencies acquired when the parent technologies were developed. The hybridization with existing technologies allows the firm to enhance its competences by combining the new technology with the existing knowledge base. To put it briefly, if we assume that the new technology is a set of *competence enhancing* technologies, firms with large knowledge bases have strong incentives to invest in nano S&T. Therefore the degree of firm specialization should remain stable as the firm invests in a new field *i.e.* as the size of the knowledge base increases.

If nanotechnologies are competence destroying activities in their early stages, as was the case with biotechnologies, the development of research in nano S&T will alter the coherence of the knowledge base and the efficiency of large firms. Thus, they do not heavily invest in nano S&T, but prefer to ally with specialized firms to explore their potential. The degree of specialization decreases with the size of the firm knowledge base. On the contrary, if nanotechnologies are competence enhancing technologies, based on hybridisation with existing technologies, large firms will have a competitive advantage in the development of nano S&T. The development of nanotechnologies does not alter the coherence of the knowledge base, and therefore the degree of specialization in nano S&T remains stable while the size of the knowledge base increases. This statement however needs some qualification. New firms, starting from scratch to exploit results from nano S&T research will of course be highly, even fully, specialized. It is doubtful that incumbents will reach such a degree of specialization, as their knowledge bases are diversified and related to different fields. For some of these fields, nanotechnologies may have little or no relevance.

Hypothesis 1: The degree of specialization in nano S&T decreases with the size of the firm's knowledge base.

Hybridization and the diversity of the nano knowledge base

Nano S&T field has been developed through the convergence of different scientific and technological existing fields. The nano S&T part of firms' knowledge bases are thus heterogeneous in terms of the scientific and technological fields connected to it. In this paper, heterogeneity is characterized by measuring the *diversity* of the nano knowledge base *i.e.* the diversity of technologies involved in the dedicated nano activities within a specific firm. The diversity depends upon the size of the nano knowledge base. However, the size of the nano knowledge base may cover two different situations. **Either**:

1. The additional project is developed through hybridisation of the new technology with the existing knowledge base. When a new project is added to a firm's research portfolio, the scope of its knowledge base will tend to increase. However, if the project is closely related to the firm's on-going projects or to the parent technologies, the effect on the coherence of the knowledge will be limited. The existing knowledge base is reinforced as the firm combines nano S&T with its competences in different fields in each project (hybridization). Note that hybridization implies that it is not necessary to have a large knowledge base to achieve diversity. Indeed, if each and every item in the knowledge base is at the frontier of many fields, even small knowledge bases can be highly diversified; **or**

2. In contrast, if nano S&T are developed as a radically new field, there is no hybridization, and the development of nano S&T increases the diversity of the knowledge base. As nano S&T are developing as an independent field, we label this situation as juxtaposition of nano S&T to existing activities. The absence of hybridization includes two situations (or a combination of the two): either the firm

combines nano S&T with the different fields in its knowledge base separately or its activities in nano R&D are just added to the knowledge base without synergies. This pattern was observed in biotechnology, where the diversity of firms' knowledge bases increased strongly during the emerging phase. If the development of nano S&T follows the same pattern as that of biotechnology, the research diversity within Nano S&T should increase with the nano knowledge base size. This discussion of hybridization vs. juxtaposition leads us to formulate two conflicting hypotheses.

Hypothesis 2: Where nano S&T is developing through hybridisation, diversity within nano S&T remains stable when the size of firm's nano knowledge base increases.

Hypothesis 3: Where nano S&T is integrated in firm's knowledge base through juxtaposition, the diversity of the knowledge base within nano S&T increases with the nano knowledge base size.

It is crucial to assess to what extent diversity results from juxtaposition or hybridization. Indeed, it has strong implications for the coherence of firms' knowledge base as well as for the economies of scope that firms can expect when investing in nanoR&D. If a firm is able to hybridize, it can expect significant economies of scope thanks to the development of the nano aspects of its R&D. But if nano S&T are developed through juxtaposition, the economies of scope will be lower.

4. Data Description and Methods

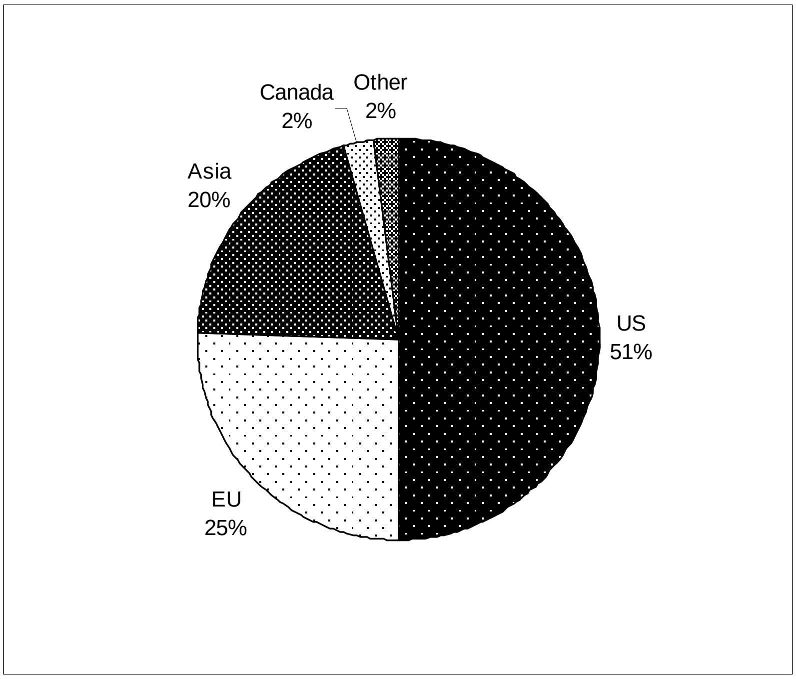
In order to describe the development pattern of commercial nanotechnologies, we built a worldwide database of nanofirms, including information on their publications and patents as well as financial information over the period 1992-2004. The evolution of research activities within firms has been mapped through publication data, while the pattern of technological innovation has been analysed through patents.

After having described the data collection strategy and how the database was built, we discuss the world distribution of nanotechnology firms and corporate nano-patents and nano-publications, and describe the variables used to explain the firm knowledge base.

Nanofirms: a global perspective

Since the classifications used for firms by the national bureau of statistics ignore Nano S&T as an independent domain, a specific strategy to identify firms involved in nanotechnologies and to build a firm database is required. The list of nanofirms is based on three sources: (1) the firms which filled a patent in the nano S&T fields at the US patent office (USPTO); (2) The firms which publish an article in a journal linked to nano S&T which is listed in the ISI database 'Web of Knowledge'; (3) the firms listed in two databases – NanoVIP and Nano-Invest. The search strategy for nano S&T patents and publications was based on keywords using the search equation designed by ISI-Fraunhofer (Fraunhofer-ISI, 2002, Noyons *et al.*, 2003). The whole database counts 3091 companies. 1051 have at least one nano-patent and 1195 at least one nano-publication.[4] Figure 1 provides a description of the geographical distribution of nanofirms between large regions in the world, and shows that one nanofirm out of two is located in the US, one out of four in Europe and one out of five in Asia. (Details on the distribution within Europe and Asia can be found in appendix.)

Figure 1: Geographic distribution of nano-firms



[4] Additional firms were identified through various websites and reports leading to a list of approx. 3,000 firms in the world. However, we do not consider here firms with no patent or publication.

Corporate nano-patents and nano-publications

The publications in nano S&T include all papers related to nanotechnologies indexed in the Thomson-ISI database ‘Web of science’ from 1993 to 2003. Around 122,000 publications have been identified. The data on nano-publications has been obtained through the use of sophisticated scientometric methods which have improved the basic bibliometric method (Meyer *et al.*, 2001). The scientometric methodology is a two-stage method based on key words, which are used to download all publications related to nano S&T. The first extraction made through keywords is controlled using citation method to estimate the centrality of publications within nano S&T (Zitt *et al.*, 2006).

After having controlled for the relevance of the database on publications, 1195 firms were identified as publishing in nano S&T. Firms’ publications reveal the involvement of firms in science production. The firms identified as nano-firms published about 15,000 articles over the 1993-2003 period.

Figure 2 shows the evolution of the number of nano-publications over the period. Corporate production of nano S&T publications can be seen as both sustained and increasing over the period, with a significant difference between pre-1999 and post-1999 years. (Figures for 2003 should not be interpreted as the sign of a decrease in the number of nano-publications but rather as a consequence of delayed updating of publications in the Science Citation Index.)

Figure 2: Corporate nano-publications

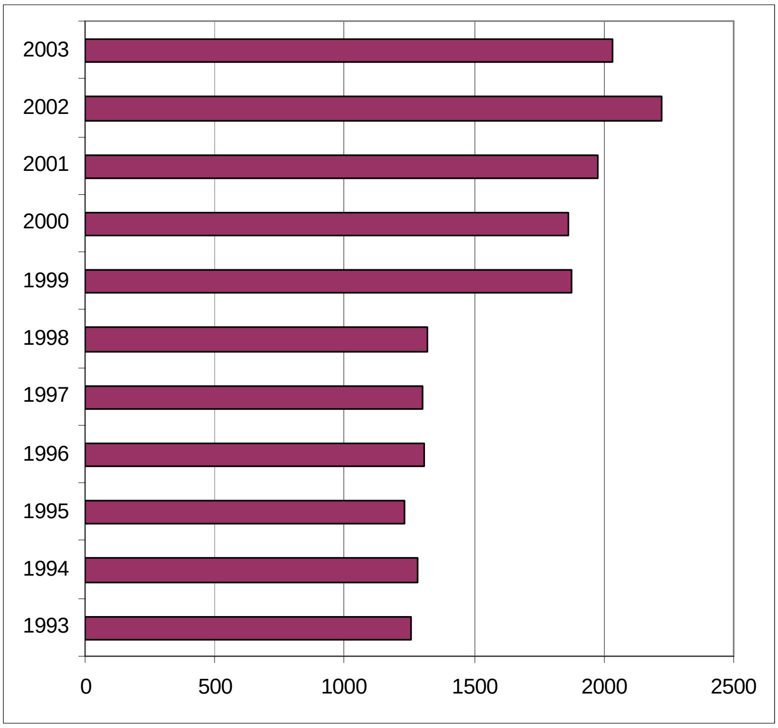


Figure 3 provides the distribution of corporate nano-publications between world's regions (see in appendix the distribution between countries in each region). The share of the different geographic areas between regions is very different from the ranking based on the number of firms. Indeed, while Asia represents 20% of firms, it produces 39% of publications in the nano-field (about as much as the US).

Figure 3: Geographic distribution of corporate nano-publications

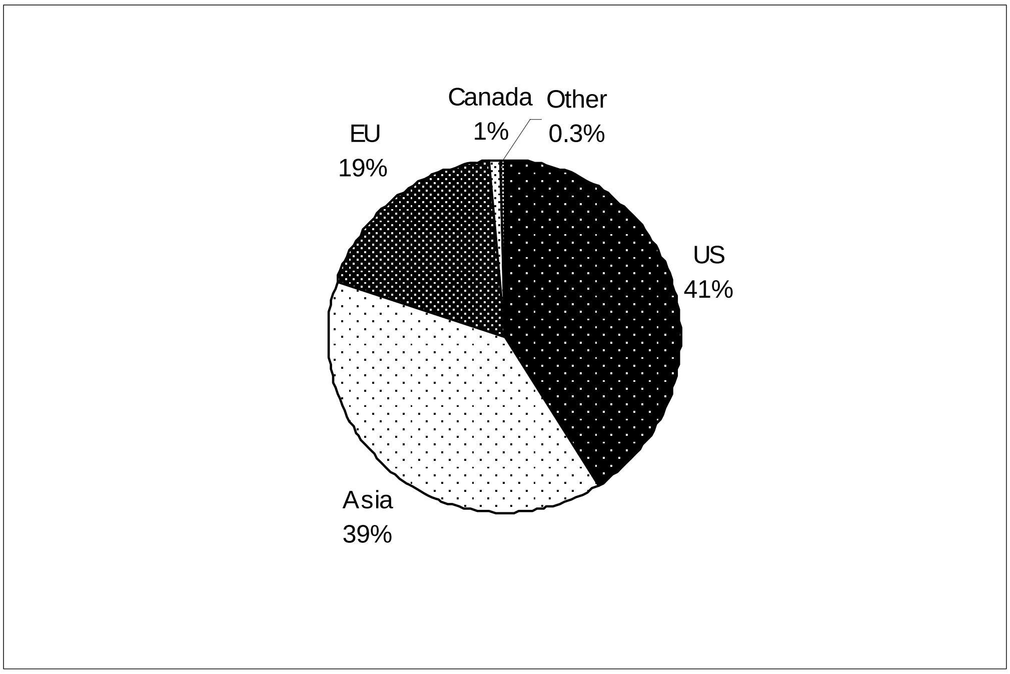
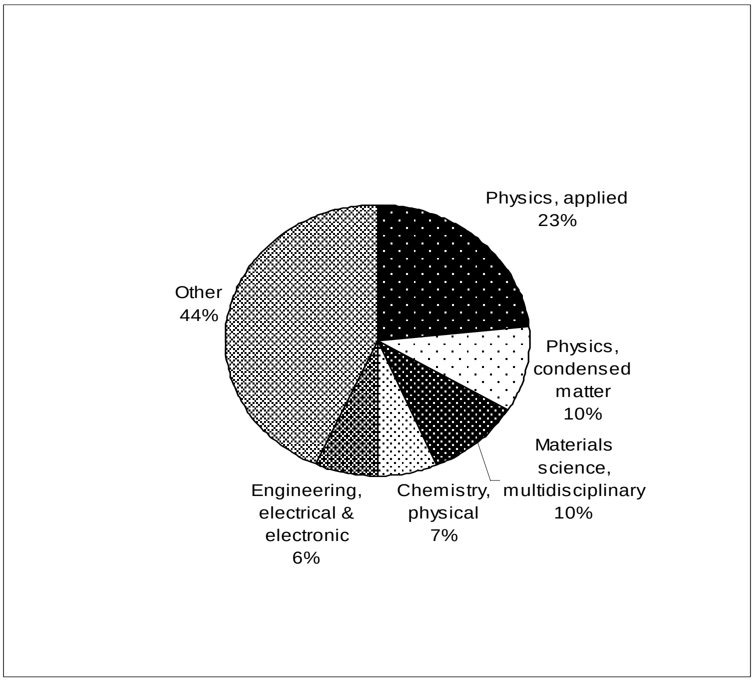


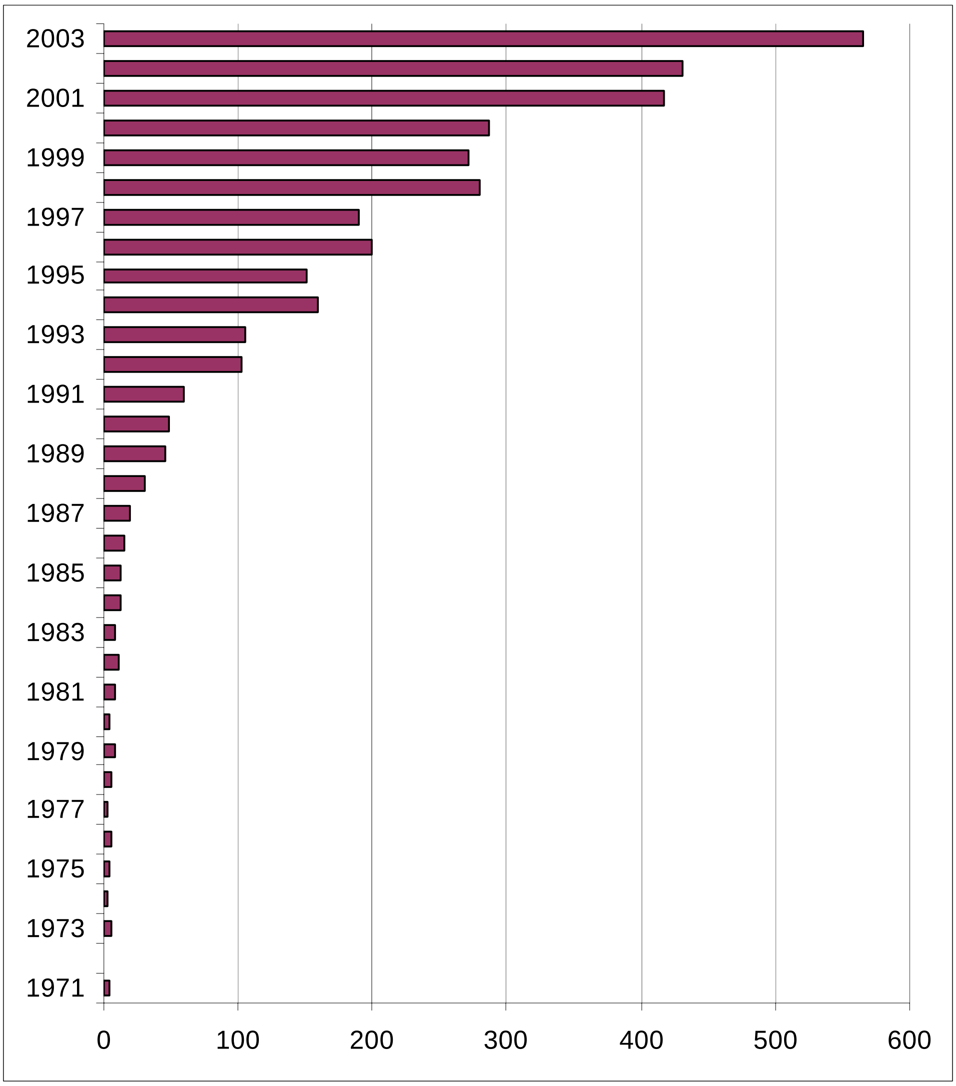
Figure 4 describes the distribution of nano-publications between scientific fields, based on the ISI Journal Classification system. This provides an interesting view of the transversality of nano, with links to physics, materials science, chemistry and engineering.

Figure 4: Nano-publications by categories



The data on the number of nano-patents, patent titles, inventors, research fields, and location of research was obtained from patents information of the USPTO. The extraction from the USPTO (including the use of the TAG nano defined ex post) forms a sample of 4,000 nano-patents. The second stage of data collection on patents was to identify all the patents filed by the firms which filed at least one nano-patent. Figure 5 shows the evolution of the number of nano-patents over time. It shows a sharp increase. In fact, nano-patents are very rare until the late 80's. After 1989, there is a clear take-off and an impressive growth in the number of nano-patents.

Figure 5: corporate nano-patents



The geographical distribution of nano-patents (see figure 6 and appendices for details on Asia and Europe) shows that the weight of US is stronger than for the number of firms, while the share of Europe is clearly lower. This suggests that while firms in Asia publish more than firms elsewhere, US firms outperform their competitors in patenting. Such evidence requires careful examination: The work on USPTO introduces a bias in favour of US firms. Moreover, US headquarters of multinational firms may be the assignees for patents developed in foreign affiliates. Patent data doesn't reflect exactly the R&D activity that is taking place in the various countries.

Figure 6: Geographic distribution of corporate nano-patents

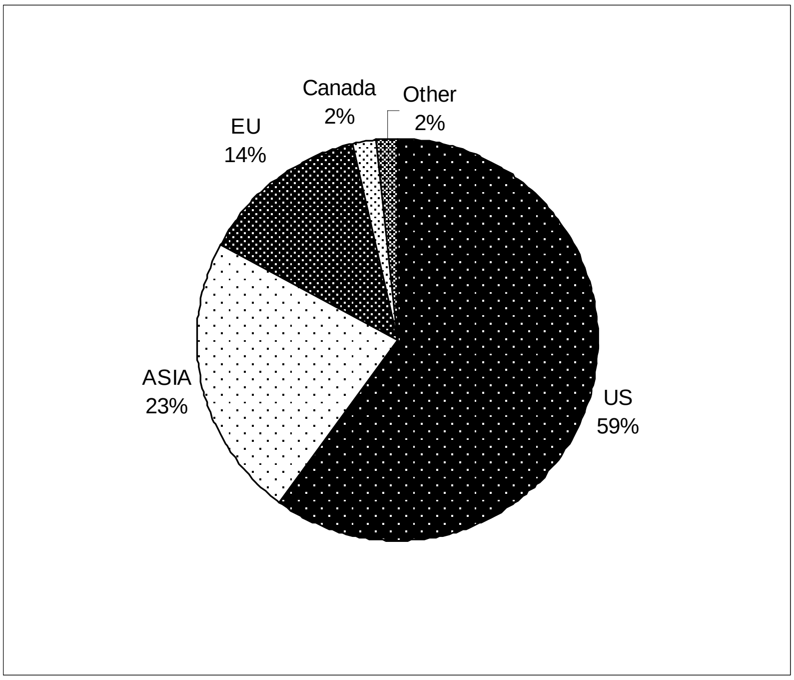
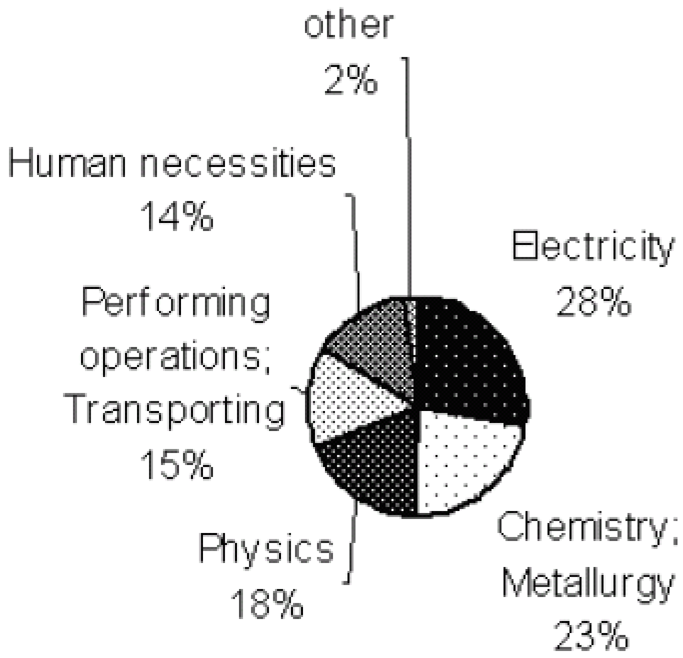


Figure 7 provides the distribution of nano-patents between the various (aggregate) fields of the International Patent Classification (http://www.wipo.int/classifications/ipc/en/). It is difficult to compare with figure 4 because the classification is different. It is interesting to note the very significant share of 'electricity' as well as the presence of 'human necessities' in the five fields that represent 98% of nano-patents.

Figure 7: Nano-patents by technological fields



Characterizing the knowledge base of nanofirms

To test the hypotheses on the early stages of development of firms' knowledge base in nanotechnologies, the characterisation of the knowledge base has to be translated into variables which approximate the size of the knowledge base, the degree of specialization, the diversity of the knowledge base and the hybridization. Variables must be estimated through data collected in the database. These variables will be used in section 5 to test our hypotheses and to lead regression analysis. The rest of this section is devoted to the description of variables.

To characterize the firm knowledge base, we count the number of patents and the number of publications of each firm. The variables are defined as:

NBPUBN = number of firm's nano-publications

NBPATN = number of firm's nano-patents

NBPATN89 = number of firm's nano-patents filed between 1989 and 2003

NBPATNP89 = total number of firm's non-nano-patents filed between 1989 and 2003

NBPATT89 = NBNPATN89+NBPATNP89

Since there were very few nano-patents issued before 1989 (see figure 5), NBPATT89 is used in conjunction with NBPATN89 to measure post-1989 firm specialization in nanotechnonolgies. Counting total patents before this date would bias the measure of specialization downwards.

Table 2 provides a description of the variables distribution

Table 2: Firm's nanotechnology publications and patents'

	NBPUBN	NBPATN	NBPATT89
N	1 195	1 051	998
MEAN	14.1	3.66	695.6
Q10	1	1	1
Q25	1	1	5
Q50	3	1	31.5
Q75	9	3	293
Q90	24	6	1513

The differences between means and medians indicate that there are firms with very big knowledge bases in the sample. The top ten percent of publishing firms publish at least 24 articles each and the top ten percent of patenting firms were issued at least 6 nano-patents each (out of 1513 patents overall) since 1989. In the same time, fifty percent of publishing firms have 3 or less publications and fifty percent of patenting firms have 1 nano-patent and less than 32 patents (issued since 1989). There is thus a huge diversity in the scientific and technological profile of firms in the sample.

Five additional variables describe the firm knowledge base: the Specialization index (SHARE), the Diversity indexes of patents and publication (DIVPATN and DIVPUBN) and the Hybridization indexes of patents and publications (HYBPATN and HYBPUBN). Table 3 summarizes these variables and table 4 provides the quartiles of their distributions. Variables related to patents are calculated only for firms with at least one nano-patent and variables related to publications for firms with at least one nano-publication.

Table 3: Definitions of variables

	Specialization of firm's knowledge base in nano	*Diversity* of firm's nano knowledge base	*Hybridization* within firm's nano knowledge base
Patents	SHARE=NBPATN89/ NBPATT89	DIVPATN=1-HHI_{PAT}	HYBPATN=FIELDS/ NBPATN
Publications	n.a.	DIVPUBN=1-HHI_{PUB}	HYBPUBN=CAT/ NBPUBN

Specialization index (SHARE): the specialization index is the proportion of firms' nano-patents as a percentage of the total number of their patents, ranging from 0-100%, with a larger value indicating a more specialised firm. Because of the scarcity of nanopatents before 1989, the specialization index is calculated using only patents issued between 1989 and 2003: counting patents before this date would bias the measure of specialization downwards. Once again, the quartiles reveal wide variations between firms. On average, about 25% of a firm's patents are in nano S&T, but firms in the top decile are fully specialized, having only nano-patents, while for one firm out of two in the sample. nano represent less than 6 percent of patents.

The specialization index approximates the technological specialization of nanoR&D. We cannot calculate the (scientific) specialization index for publications because we don't have the information on the non-nano-publications of the firms.

Table 4: Descriptive variables

	DIVPATN	DIVPUBN	HYBPATN	HYBPUBN	SHARE
N	1 051	1 195	1 051	1 195	998
MEAN	0.41	0.57	1.57	1.56	25.66
Q10	0	0	1	1	0.22
Q25	0	0	1	1	0.74
Q50	0.50	0.50	1.45	1.5	5.79
Q75	0.67	0.67	2	1.9	40
Q90	0.79	0.80	2.33	2	100

Diversity indexes (DIVPATN and DIVPUBN): Both the scientific and the technological sides of firms' activities can be located in different research fields, either because the firm addresses various fields separately or because its research activities cross several fields. The diversity indexes measure the breadth of a firms' nanoR&D activities to ascertain whether they are concentrated in a small number or spread over a larger number of fields. To define the fields, we rely on the International Patent Classification for patents and the ISI Journal

Classification system for publications. Borrowing a tool used in industrial organization to measure market concentration, we take 1 minus the Herfindahl index as our diversity index. The diversity index is comprised between 0 and 1. The degree of diversity increases with the value of our index. When the index is equal to 0, the firms focuses its entire nanoR&D on a unique field. In the same way, if the firm spreads its NanoR&D into a very large number of fields, the index will be close to 1. This is however a more theoretical than practical possibility. In the sample, we don't observe indexes larger than 0.8, which still implies a very high level of diversity. It is interesting to note that one firm out of four focuses its entire activity on one field only. In the regression analysis, we will also use DIVPATO, the diversity index calculated for non-nano patents issued since 1989.

Hybridization indexes (HYBPATN and HYBPUBN) To measure the extend to which firms exploit the opportunities that nanotechnologies create to organize the convergence of difference fields within their research projects, the hybridization index counts the number of different research fields (categories) quoted on average by each patent and publication of a specific firm. The variable CAT is calculated summing over all publications the number of scientific categories quoted by each publication. The variable FIELDS is calculated similarly for the technical fields quoted by each patent.

The index is a real number larger than or equal to 1. The larger the value of the index, the higher the degree of hybridization. On average, each patent or publication in a firm's knowledge base quotes 1.5 categories, but for one firm out of four, each item quotes only one category. For firms in the top quartile, the degree of hybridization is significantly larger with each item quoting at least 2 categories on average.

5. Results

Hypothesis 1 states that the degree of specialization in nano S&T decreases with the size of the firm's knowledge base. To test it, we plot (see figure 8) the variables *Specialization index* (SHARE) (on the y-axis) and (the decimal logarithm of) the *total number of patents issued since 1989* (NBPATT89) (on the x-axis). Contrary to our hypotheses, Figure 8 shows a clear decrease in the degree of technological specialization in nano S&T when the size of the knowledge base increases. The rejection of our first hypothesis can be interpreted in different ways: Either nano S&T are not as competence enhancing as we assumed, but are similar to biotechnology in their effects on the firm's knowledge base. Or nano S&T are not as transverse as we claimed. Note that some firms in the sample have a huge knowledge base, which suggests a large diversity. It seems reasonable to assume that such knowledge bases reach far beyond the domain on which nanotechnologies may have an impact. Note that the decreasing shape of the scatter plot may result from the combination of both phenomena. However, one should keep in mind the fact that nano are still at an early stage and that firms certainly did not yet explore all the possibilities that nano offer to them. The degree of specialization may well change dramatically in the future. Case illustrations 1 and 2 represent respectively the profile of a small, specialized firm (CNI) and a huge, diversified firm (BASF).

Figure 8: specialization and size of the knowledge base

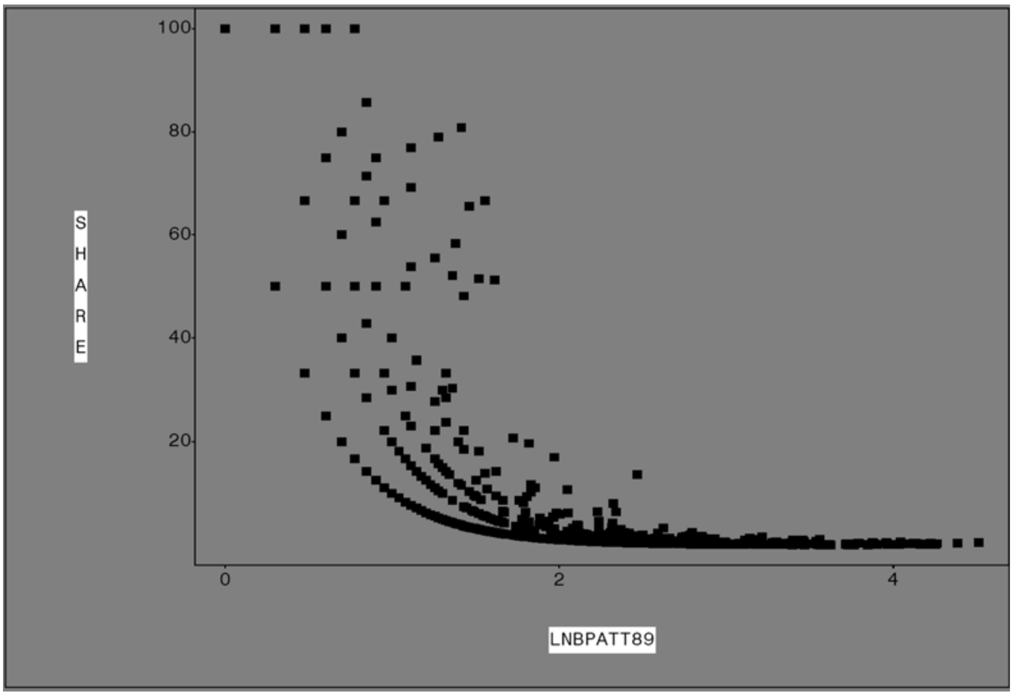


Figure 9 represents the evolution of diversity when the knowledge base of the firm increases. It plots the diversity index of patents (DIVPATN) on the ordinate axis and the decimal logarithm of the total number of patents (NBPATN) on the abscissa axis. Colours on figures indicate the total number of patents between 1989 and 2003 by quartiles, with darker colours indicating larger numbers of patents. Hypothesis 3 suggests an increasing relation between the two variables, but this is not observed in figure 9. Indeed, there are very few firms below the 45 degree line, which means that firms with a large nano knowledge base also have a diverse nano knowledge base, which tends to support hypothesis 3 more than hypothesis 2. As nano S&T is integrated in firm’s knowledge base through juxtaposition, the diversity of the knowledge base within nano S&T increases with the nano knowledge base size. However, an unexpected finding is there is a quite significant set of firms above and on the left of the 45 degree line, that is, firms with a small but diverse knowledge base. This suggests that nano S&T is also developing through hybridisation, as the diversity within nano S&T remains stable when the size of firm's nano knowledge base increases. This tends to support hypothesis 2 more than hypothesis 3. So, if a firm has a large knowledge base, it will be diversified, but it is not true that if a firm is diversified it will necessarily have a large knowledge base. We find small firms which are diversified, and the same level of diversity is achieved by firms which differ a lot as regards the size of their knowledge base: there are clearly several possible firm profiles in the nano industry. And as far as hypotheses 2 and 3, are concerned, we cannot confirm or reject either.

Two patterns co-exist in the emerging nano fields, one in which diversity is linked to size and one in which it is not. While it is easy to figure out a mechanism generating the first pattern, such as the juxtaposition of unrelated nanoprojects, the second one appears to be more difficult to explain, where the expansion of the knowledge base is realised through hybridization.

Figure 9: diversity and size of nano-knowledge base (patents)

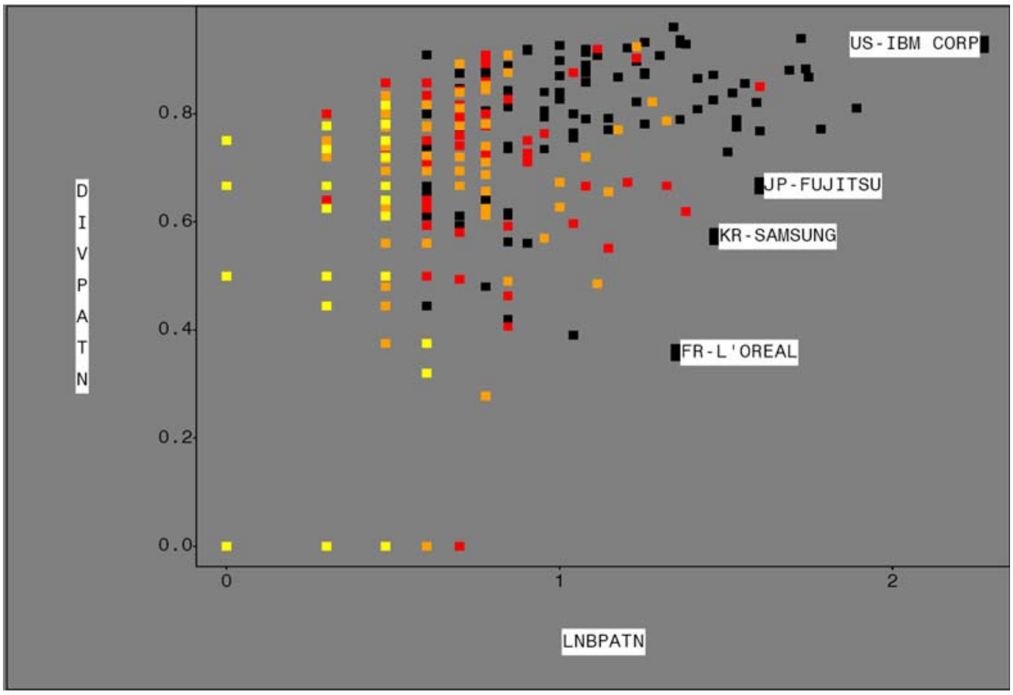
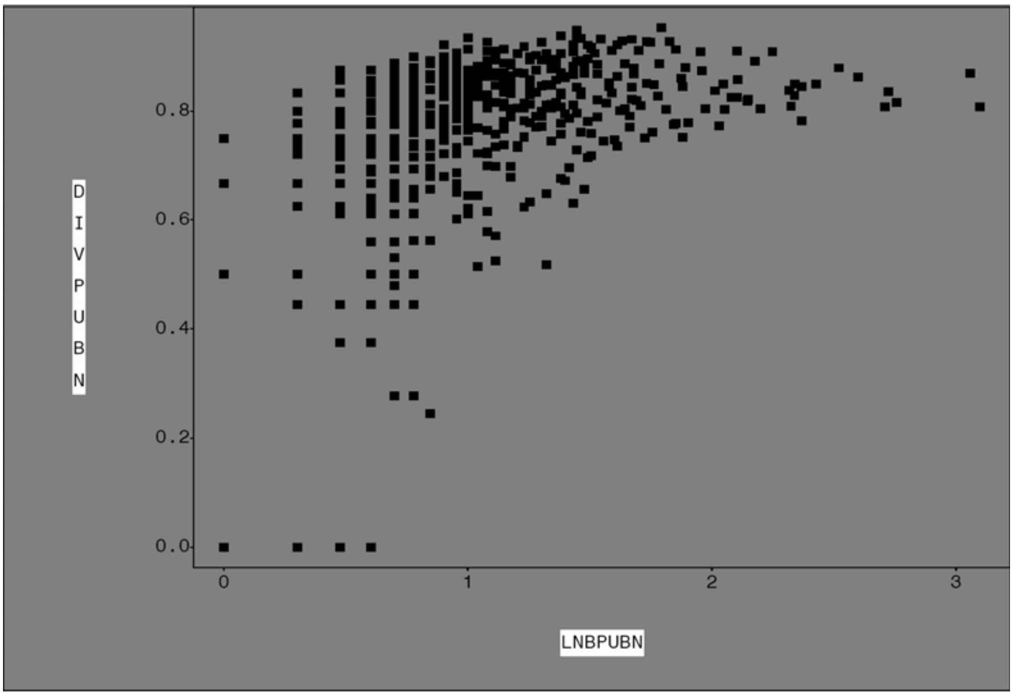


Figure 10 displays a similar pattern to Figure 9, representing the diversity of publication compare to the size of the knowledge.

Figure 10: diversity and size of nano-knowledge base (publications)



As nanotechnologies have been defined as converging technologies at the crossroad of different scientific and technological fields, how to internalise nano S&T diversity remains a central question for firms. To examine further the issue as to how firms of different size achieve diversity, we plot the values of the hybridization index and the diversity index for the firms in our sample. This leads us to figures 11 (patents) and 12 (publications). Colours correspond to the number of respectively nano-patents (1 to 2 for the lightest, 3 to 4, 5 to 6 and more than 6 for the darkest) and nano-publications (1-2 for the lightest, 3 to 4, 5 to 10 and more than 10 for the darkest).

Figure 11: diversity and hybridization (patents)

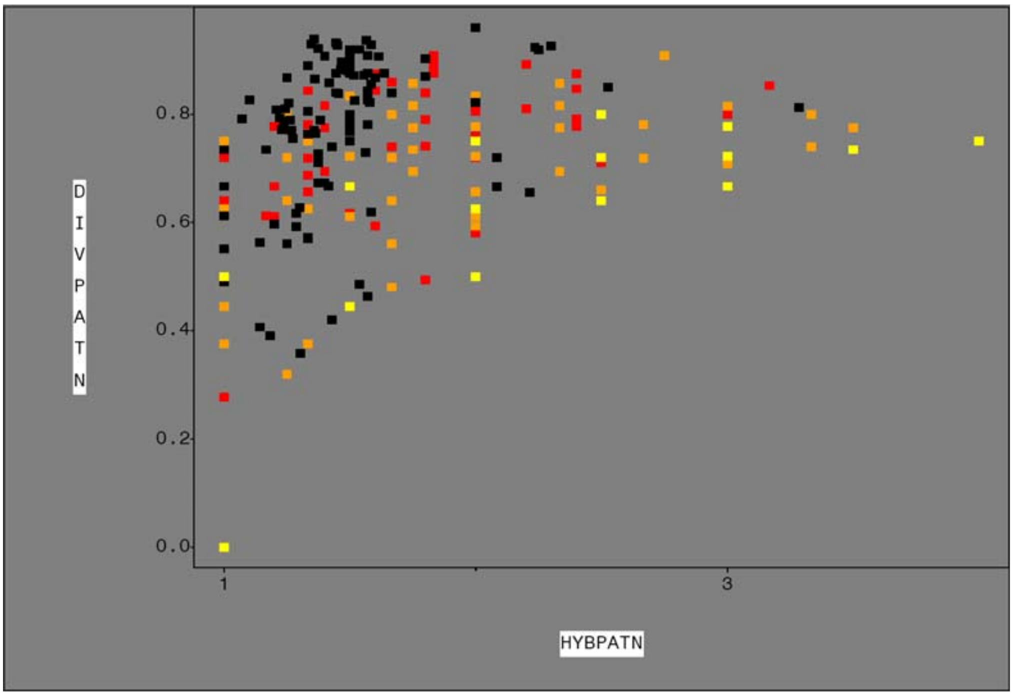
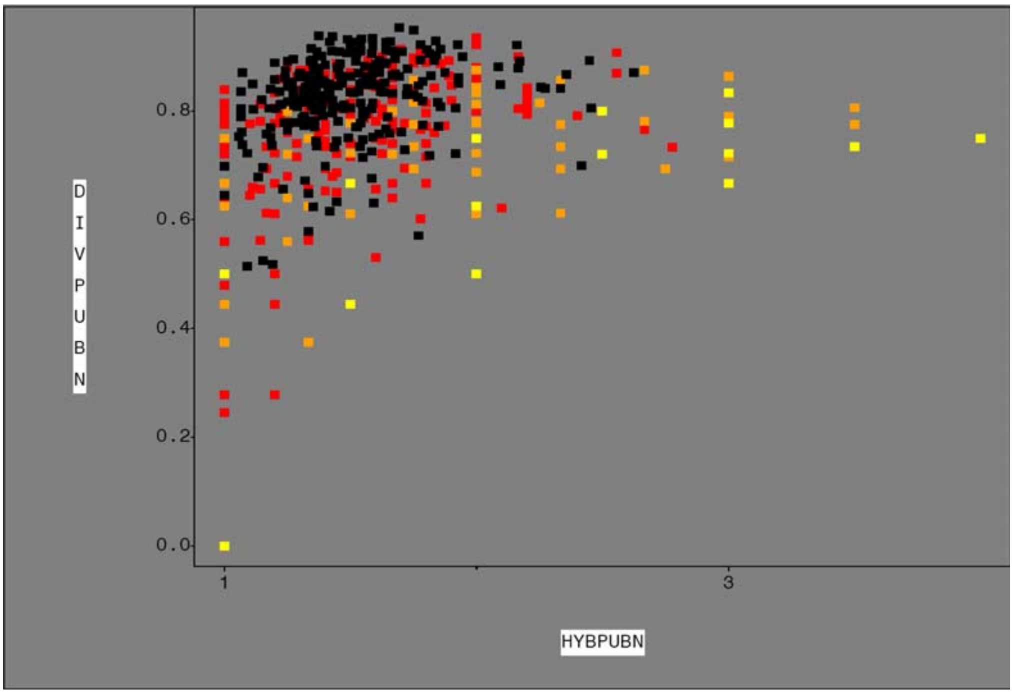


Figure 12: diversity and hybridization (publications)



Figures 11 and 12 show that while firms with large knowledge bases exhibit limited degrees of hybridization (and thus cluster on the top left of the figure), some small firms reach very high degrees of hybridization, which makes it possible for them to build diversified knowledge bases based on a limited number of patents or publications. The two case illustrations demonstrate these two patterns.

Hybridization allows firms to exploit its competences in different fields as it is based on recombination of existing competencies. To what extent the degree of specialisation in nano S&T (SHARE) is linked to the mechanisms of integrating nano S&T within the firm knowledge base? To what extent the characteristics of nano S&T influence the ways that firms integrate and/or specialise within the nanofields? The determinants of specialization can be analysed by estimating the following equation:

$$SHARE=a_0+a_1*\log(NBPATT89-NBPATN89)+a_2*HYBPATN+a_3*DIVPATO$$

The equation estimates the share of nano-patents within the firm knowledge base. To avoid endogeneity biases, nano-patents have been excluded from the exogenous variables which are defined as the total number of non-nano patents (NBPATT89--NBPATN89), the diversity of the non-nano technological knowledge base (DIVPATO) and the hybridisation index of patent (HYBPATN) as it assesses the impact of the hybridization on the knowledge base. Table 5 shows the results of the OLS estimation of the equation.

Table 5: OLS estimation

	SHARE
ln(NBPATT89-NBPATN89)	-8.5677* (-17.56)
HYBPATN	0.8910** (2.08)
DIVPATO	-30.8383* (-12.94)
Constant	50.2511* (30.28)
R^2	0.6197
F	454.08
n	839

Figure in parentheses are t-statistics.
(*) significant at 1%, (**) significant at 5%

This model explains the specialization of firms in nano S&T. The regression analysis disentangles the respective impact of the different variables. Figure 8 reveals a sharp decrease in the degree of technological specialization in nano S&T when the size of the knowledge base increases. It may reveal either that nano are competence destroying technologies or they are not so transverse as expected, or both. The regression shows that both the size of the knowledge base and its diversity have significant, negative impacts on specialization in nano. This suggests that nano are competence destroying (at least for part of firm's competences) and that at the same time there are limits to its transversality. This raises questions about the comparative advantage of incumbents. Indeed, investing in nano R&D will lead to significant changes in the structure of their knowledge base and reduce its coherence. From Nesta and Saviotti (2005), we know that this is not a favourable change.

Turning to the impact of hybridization, Table 5 shows the expected clear positive impact on specialization. This suggests that new, hybrid scientific and technological trajectories are emerging and that the firms who identify and follow these trajectories them will boost their R&D effort substantially. As shown by figure 11 and 12, these are mainly small firms that follow this approach to nanotechnology. To sum up, small firms may be all the more specialized as they have small, limitedly diversified knowledge bases and as they (at least some of them) achieve a high degree of hybridization.

The picture we draw here is very much one of a Grilichesian breakthrough as defined in Darby and Zucker (2003) with scientific breakthroughs leading to the emergence of a new field, competence destroying technologies and emerging new trajectories. This is very similar to what we could observe in biotechnology twenty years earlier so that it is tempting to conclude that we will play the same game again and that start-ups will be the main players in nano R&D. However, this conclusion needs very serious qualification. It should even be rejected. After all, we see that huge firms are investing heavily in nano R&D. From the point of view of knowledge management, they probably should not be so implicated in nano. However, the development of nano is not only determined by the logic of knowledge management. Indeed, one of the peculiarities of nanotechnologies as compared to biotechnology is that in nano there is from the start a crucial need of access to huge research facilities (like clean room and microscopes). Start-ups cannot afford the enormous investment needed to create these facilities. Large incumbents can do so and indeed they do. The similarity here is not with biotechnology but rather with microelectronics. It seems reasonable to conclude that what is emerging now in nano is neither the pattern of biotechnology nor the pattern of microelectronics but a mixture of these two patterns in which there is space for both start-ups and incumbents in the R&D activity.

6. Conclusion and Discussions

Based on the worldwide database of nanofirms, the paper examines the development pattern of Nano S&T. It argues that firms integrate nano S&T by juxtaposition of new projects around the existing ones and by hybridisation of new technologies with existing technologies within the firm. Large firms mainly follow the first path while small and specialised ones (Nano-dedicated firms) develop new projects through hybridising with existing knowledge base. Nano S&T appear to be less transverse and competence enhancing than specialised and competence destroying as new competencies replace the existing ones within firm knowledge. The firm knowledge base is not the locus of the convergence as expected.

As nano S&Ts are developing by the addition of new and juxtaposed projects within large companies, the development of nano S&T will decrease the coherence of the knowledge base of incumbents and it may reduce the propensity to innovate of those firms, given a premium to small dedicated nanofirms. However, nano S&T remain different from the biotechnology model in three respects:

(1) Existing firms are developing nano S&T linked to their existing knowledge base. It is an extension of the parents' technologies contrary to the biotechnology case in which it radically transforms it (Zucker *et al.*, 1997). Incumbents benefit from their existing knowledge base, their existing networks and their learning capabilities. The advantage of science based start-ups may be lower than the advantage of those companies in biotechnology (Klepper *et al.*, 2005a; Klepper *et al.*, 2005b).

(2) Access to existing research and production facilities is a key asset in nano S&T as it is built on existing technologies. It is particularly the case in nanoelectronics with the access to large facilities like in Minatec or Albany. But it is also the case in nanobiotechnologies with the access to facilities developed in universities and firms.

(3) Due to the key role of research facilities, the development of nano S&T and nano firms may be even more geographically polarised to that it has been in biotechnology.

The nano S&T patterns of development combines competence destroying activities and the critical role of research facilities and technological platforms which can be analysed as specialized complementary assets which improuve incumbent performance when a radically new technology is introduced (Rothaermel *et al.*, 2005).

The engine of development of nanotechnologies may be even more polarised than in the biotechnology industry, combining the proximity to centres of scientific excellence with the access to state of the art facilities and platforms, be public or private (Steinle, 2002 #3471; Agrawal, 2003 #7839). The challenge for policy makers, especially regional authorities is even higher to attract nano S&T related activities.

7. References

Abernathy WJ, Utterback J. 1978. Patterns of Industrial Innovation. *Technology Review* **80**: 41-47

Boisot MH. 1995a. Is Your Firm a Creative Destroyer - Competitive Learning and Knowledge Flows in the Technological Strategies of Firms. *Research Policy* **24**(4): 489-506

Bonaccorsi A. 2005. Search regimes and the industrial dynamics of science. *Working paper*

Breschi S, Lissoni F, Malerba F. 2003. Knowledge-relatedness in firm technological diversification. *Research Policy* **32**(1): 69-87

Darby M, Zucker L. 2003. Grilichesian Breakthroughs: Inventions of Methods of Inventing and Firms Entry in Nanotechnology. NBER, Working Paper 9825

Fraunhofer-ISI. 2002. Search Methodology for Mapping Nano-Technology Patents. ISI: Karlsruhe

Henderson R, Cockburn I. 1994. Measuring Competence - Exploring Firm Effects in Pharmaceutical Research. *Strategic Management Journal* **15**: 63-84

Hill CWL, Rothaermel FT. 2003. The performance of incumbent firms in the face of radical technological innovation. *Academy of Management Review* **28**(2): 257-274

Klepper S, Simons KL. 2005a. Industry shakeouts and tcehnological change. *International Journal of Industrial Organization* **23**: 23-43

Klepper S, Sleeper S. 2005b. Entry by spinoffs. *Management Science* **51**(8): 1291-1306

Mangematin V, Rip A, Delemarle A, Robinson DKR. 2005. The Role of Regional Institutional Entrepreneurs During the Emergence of Clusters in Nanotechnologies. *WP*

Meyer M, Persson O, Power Y. 2001. Nanotechnology expert group - Mapping the excellence in Nanotechnologies. ERA- Mapping the excellence: Bruxelles

Morel B, Ramanujam R. 1999. Through the looking glass of complexity: The dynamics of organizations as adaptive and evolving systems. *Organization Science* **10**(3): 278-293

Nesta L, Saviotti PP. 2005. Coherence of the Knowledge Base and the Firm's Innovative Performance. Evidence from the US Bio-pharmatical Industry. *The Journal of Industrial Economics* **LIII**(1): 105-125

Nordmann A. 2004. Converging technologies - Shaping the future of the European Societies, *HLEG Foresighting the New Technology Wave,*. EC: Brussels

Noyons CM, Buter RK, van Raan AFJ, Schmoch U, Hinze S, Rangnow R. 2003. Mapping excellence in Science and Technology accross Europe in Nanoscience and nanotechnologies. Draft report of project EC-PPN CT-2002-0001 to the European Commission: Brussels

Ramanujam V, Varadarajan P. 1989. Research on Corporate Diversification : a Synthesis. *Strategic Management Journal* **10**: 523-551

Rip A. 1997. A cognitive approach to relevance of science. *Social Science Information* **36**(4): 615-640

Rocco M, Bainbridge WS (Eds.). 2002. Converging Technologies for Improving Human Performance: Nanotechnology, Biotechnology, Information Technology and Cognitive Science. NSF: Arlington, Virginia

Rothaermel FT, Hill CWL. 2005. Technological Discontinuities and Complementary Assets: A Longitudinal Study of Industry and Firm Performance. *Organization Science* **16**(1): 52-70

Saxl O. 2005. Nanotechnology – a Key Technology for the Future of Europe. The Institute of Nanotechnology, University of Stirling: Stirling, Scotland

Shea CM. 2005. Future Management research Directions in nanotechnology: A Case Study. *Journal Engineering and Technology Management* **22**: 185-200

Teece DJ, Rumelt R, Dosi G, Winter SG. 1994. Understanding Corporate Coherence : Theory and Evidence. *Journal of Economic Behavior and Organisation* **23**(1): 1-30

The Institute of Nanotechnology. 2005. Research, Applications and Markets in Nanotechnology in Europe. The Institute of Nanotechnlogy: London

Zhang J, Baden-Fuller C, Mangematin V, Nesta L. 2005. Technological Profile and Alliance opportunity as Determinants of Exploration and Exploitation Alliances, *Academy of Management*: Honolulu, Hawaï, (USA)

Zitt M, Bassecoulard E. 2006. Delineating complex scientific fields by hybrid lexical-citation method: an application to nanoscience. *Working paper*

Zucker LG, Darby MR. 1997. Present at the biotechnological revolution: transformation of technological identity for a large incumbent pharmaceutical firm. *Research Policy* **26**(4-5): 429-446

8. Boxes and Appendices

Case illustration 1: Carbon Nanotechnologies Inc. (CNI), a typical start-up company

The company, based in Houston, Texas, was founded in 2000 by Richard Smalley, a Nobel Prize winning nanotechnology researcher, and other Rice University researchers. CNI development relies on a strong intellectual property position. It holds the exclusive license for Rice's technology surrounding carbon nanotube production and has now over 100 patents and patent applications issued or in various stages of prosecution. The issued patents provide CNI an over-arching position in all currently recognized, commercially-viable methods for the production of single-wall carbon nanotubes – or Buckytubes. CNI is a pre-eminent producer of Buckytubes. The company can provide many different grades of Buckytubes to accommodate customer-specific needs. CNI is working with close to 700 customers around the globe (leading academic research centres and a wide variety of small and large companies whose businesses depend on advanced materials).

CNI has raised major funding from private investors since 2000. In May 2001, CNI garnered $15 million in angel funding from investors Gordon Cain and William McMinn. It has also received a $3.6 million award from the federally funded Advanced Technology Program and is working closely with several government agencies on funded research projects.

In order to gain access to markets, CNI has set up multiple alliances with various partners. In 2002, the company announced plans to license its laser-oven nanotube production process technology to DuPont Central Research and Development. In 2003, CNI and NanoInk Inc. teamed up to use single-wall nanotubes in next generation nano-fabricated devices (biological sensors and semiconductor devices). The same year, CNI and DSM set up a strategic R&D alliance to explore functionalized nanotubes for boosting polymer performance. Still in 2003, CNI and Performance Plastics Products Inc. (3P) announced a joint development agreement to develop and commercialize new and improved polymer products. In January 2004, CNI signed an exclusive marketing and distribution agreement with the Japanese Sumitomo, who also announced an equity investment in CNI. This agreement enabled CNI to get access to Sumitomo's sales, marketing and established relationships with Asian customers in electronics, materials and other industries that could use nanotubes. In May 2004, CNI signed a joint development agreement with Minnesota based company Entegris Inc. to develop and commercialize new and improved polymer products. In December 2004, CNI announced its merger with C Sixty, another nanotech start-up specialized in the development of biopharmaceutical applications of fullerenes, a unique class of small molecules.

Case illustration 2: BASF, a global strategy for nanotech research and development

Among the various industrial fields potentially impacted by the development of nanosciences, the chemical industry has been especially active in integrating nanotechnologies in their innovation strategies, as shown by the case of the German chemical giant BASF.

BASF is the world's leading chemical company. In 2005, BASF had approximately 81,000 employees and posted sales of more than €42.7 billion. It has production sites in

41 countries, customers in more than 170 countries and supplies approximately 8,000 products to a wide range of industries worldwide. The firm is already one of the world's leading companies in the field of chemical nanotechnology. It is manufacturing multiple products based on nanostructures and particles and claims current annual sales for nanotechnology based products of around €2 billion.

BASF's research activities focus closely on the needs of the market, using the potential offered by new technologies to offer customers products with superior properties. Worldwide, approximately 7,000 employees work in R&D, 5,000 of them located in the central technology platforms in Ludwigshafen, Germany. In addition, the group is involved in about 1,200 cooperations worldwide with universities, research institutes, start-up companies and industrial partners. BASF has increased R&D expenditures by 8% in 2005 and is planning to raise R&D spending by a further 9% to €1.15 billion in 2006. Nanotechnology is considered by BASF as one of five key issues of particular relevance for the future (along with energy management, raw material change, plant biotechnology and white biotechnology). BASF already owns around 55 nano-related patents. It is planning to spend €180 million in research on nanotechnology for the period 2006-2008 and will open a competence centre for nanotechnology in Singapore in 2006. BASF focus its activities essentially on the manufacture and investigation of nanomaterials. BASF is also carrying out research to evaluate the risks associated with nanoparticles. For this purpose, the company is conducting its own toxicology studies, and is also involved in intercompany activities at the national and international level, together with partners from the scientific and regulatory agencies as well as the industry.

In addition to its internal research activities, BASF is developing multiple collaborations with both academic (like University Louis Pasteur in Strasbourg, France) and industrial partners (like the Japanese chemical firms Sakai and Shisheido). It is also targeting small nanotech start-up companies through venture investment done by its corporate venture capital company, BASF Venture Capital GmbH. The company has about $112 million to spend over four to five years. By now, one-third of its direct investments have been made in the nanotechnology area. BASF also participates in venture capital funds dedicated to new technologies.

Geographical distribution of nanofirms

Figure A1: Geographic distribution of nanofirms (Europe)

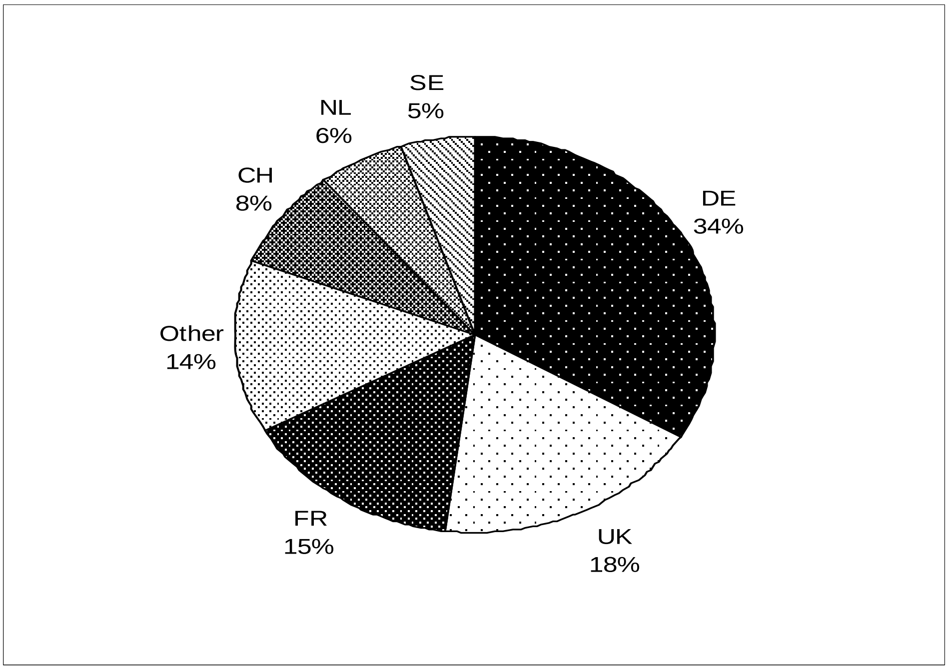
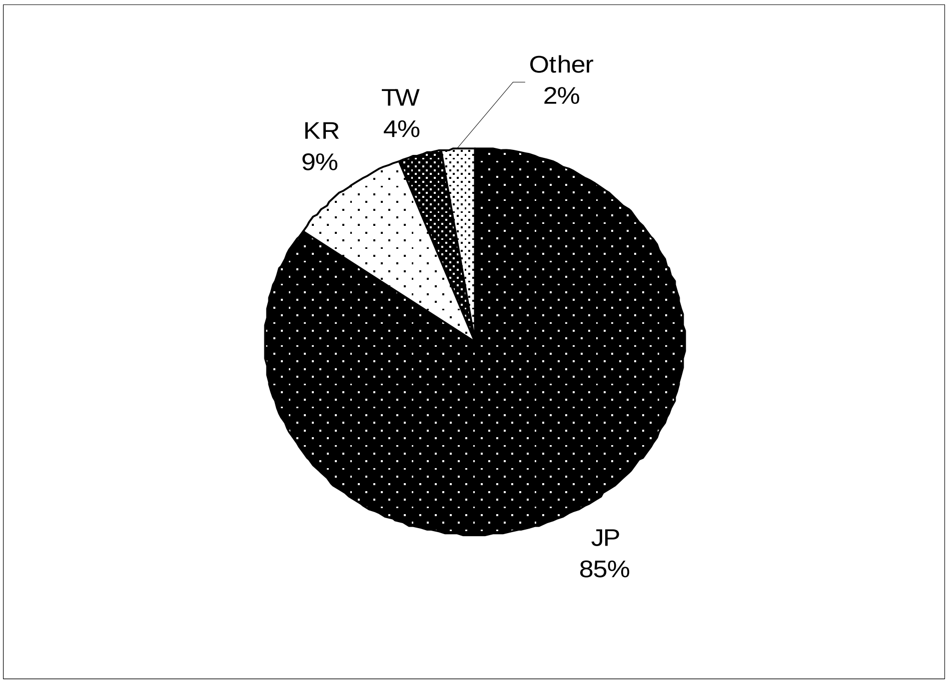


Figure A2: Geographic distribution of nanofirms (Asia)



Geographical distribution of nano-patents

Figure A3: Geographic distribution of nano-patents (Europe)

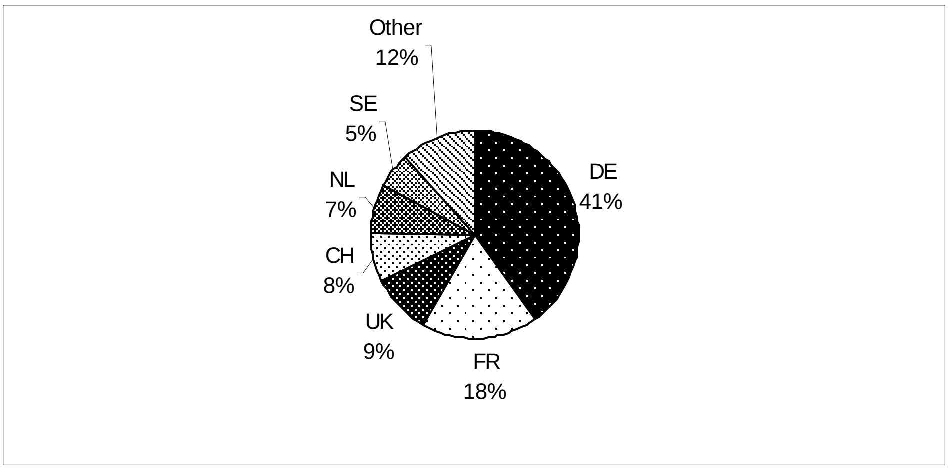
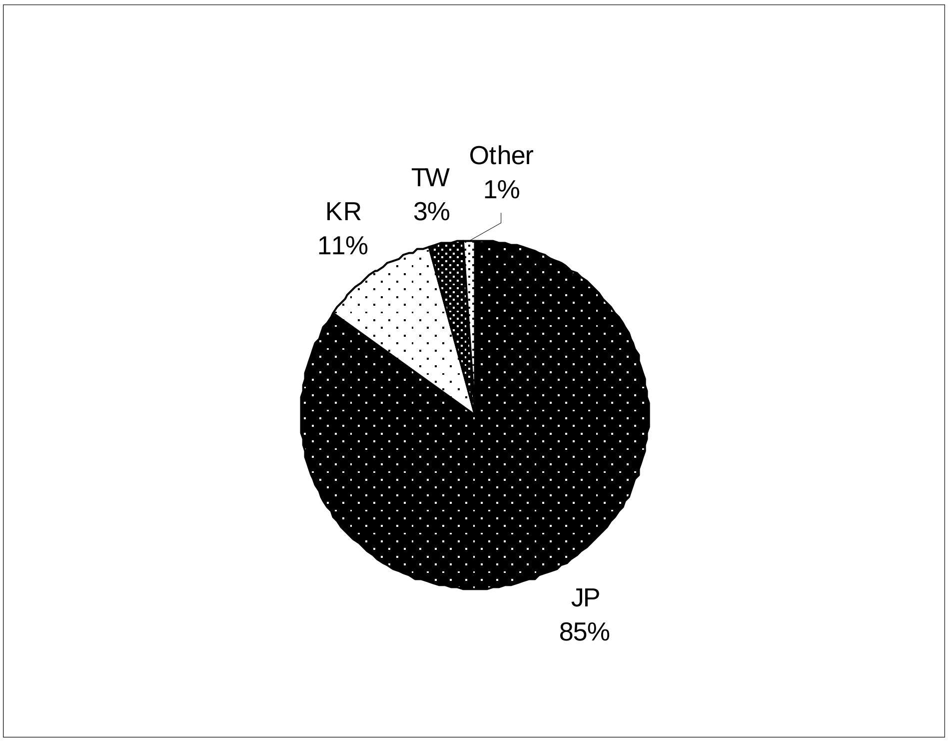


Figure A4: Geographic distribution of nano-patents (Asia)



Geographical distribution of nano-publications

Figure A5: Geographic distribution of corporate nano-publications (Europe)

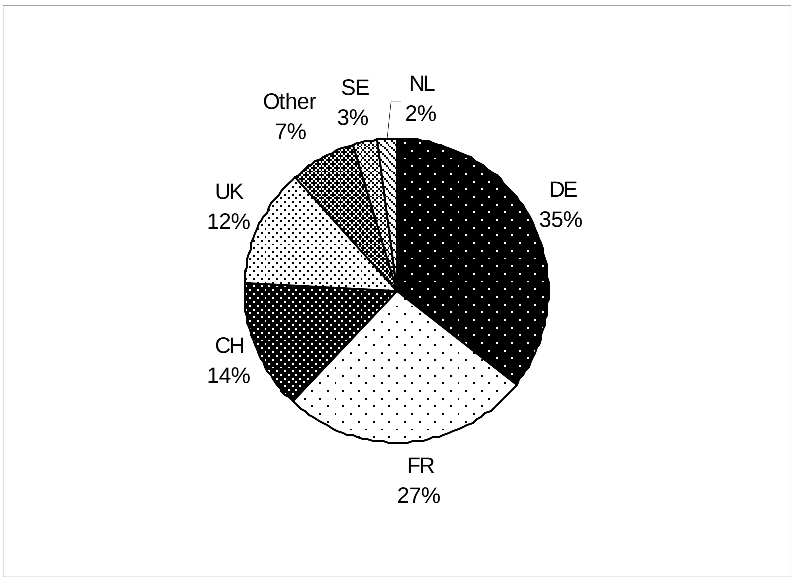


Figure A6: Geographic distribution of corporate nano-publications (Asia)