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#2011-029

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UNU-MERIT Working Papers

ISSN 1871-9872

Maastricht Economic and social Research Institute on Innovation and Technology, UNU-MERIT

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Mapping the interdisciplinary nature and co-evolutionary patterns in five nano-industrial sectors*

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Abstract

Along with the rapid growth of nanoscience research and the wide application of nanotechnology into various industrial fields, the innovation patterns and co-evolutionary natures of multiple nano industrial sectors have drawn much attention from scholars. Based on a continuously updated nano-publication database, this paper explores the learning and integrative dynamics in nano industrial sectors through the means of co-word analysis, citation distribution across sectors and institutional cooperation. We argue that the general trend of integration in nano sectors is converging in the long run, although the degree of this convergence depends greatly on the indicators one chooses. Our results show that nano technologies applied in the five studied nano industries become more diverse over time. One sector learns more and more related technologies from other sectors. The publication and citation analysis also proves that nano technology has developed to a relatively mature stage and has become a standardized and codified technology.

Keywords

Nanoscience and nanotechnology, sectoral innovation systems, interdisciplinarity, industrial sectors, publication analysis, institutional cooperation

JEL Classification

O31, O32, L52, L65

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* This paper is based on the ObsovatoryNANO project (an EU 7th Framework Program). We thank our project partners for helping with checking and refining the sectoral keyword sets.

1. Introduction

Nano scale technology has been regarded as one of the most important inventions in recent decades in creating new materials and improving industrial techniques. It enables control of matter at the molecular scale. Along with its fast development, nanotechnology has been widely applied, and is still seen to have huge potential, in various fields of research, ranging from medicine, food packaging, protective textiles, clean energy exploration, etc.

The co-evolution of nanotechnology in multiple industrial areas has shown that diverse nano innovations are becoming more and more connected. Science research at the nano scale is believed to be converging and connecting different areas of science and technology (Porter and Youtie 2009; Roco 2008; Roco 2005; Loveridge et al. 2008). As Porter and Youtie (2009) pointed out, if this convergence trend is true, it has (and continues) to have important implications not only for nano scale science but also for governance and regulations of emerging technologies. Roco (2005) states that it will bring "tremendous improvements in transforming tools, new products and services, enable human personal abilities and social achievements and reshape societal relationships".

This paper aims to explore the innovation patterns in nano industries, known as sectoral levels. The system of sectoral innovation is composed of units active in innovation activities of a sector (Breschi and Malerba 1997), and it undergoes processes of change and transformation through the co-evolution of its various elements (Malerba 2004). In the innovation system, sectors gain knowledge also from outside, through "learning by doing, learning by using and learning by interacting … technologies are not only developed, but also produced, diffused, and used" (Edquist 1997, pp. 17).

As Malerba formulates: a sectoral system has three building blocks: knowledge and technology; actors and networks, and institutions. The relationships and networks of the elements are crucial in the innovation and production process. In other words, due to the importance of learning from external fields, interdisciplinary research on technological and organizational change plays a critical role in innovation studies. The links among industries and the dynamic complementarities are believed to “provide force and trigger mechanisms of growth and innovation” (Edquist 1997; Malerba 2004).

In innovation systems studies, boundaries can be spatial, organizational, firm level or sectoral. This paper researches both sectoral (i.e. industrial specific) and organizational boundaries, where we will focus on the interactivity between related industries and cooperation between organizations.

Given the difficulty in quantifying connections and boundary changes among sectors, existing studies have shown a plethora of mixed findings in the integration level of nano fields. There has been a debate on the trend and degree of interdisciplinarity in various areas of nanoscience. One group holds positive opinions on the increasing interdisciplinarity in nano scale research and argues that nano research is getting more and more integrative (Porter and Youtie 2009; Loveridge et al. 2008). Nicolau (2004), states that “nanotechnology is the most interdisciplinary field so far. This interdisciplinarity is naturally enhanced by the fact that at the nano level the differences between very different disciplines, such as mechanics and chemistry, begin to blur to a large extent and leads to an acceleration of the knowledge production and transfer.”

Another group, on the contrary, claims that the degree of interdisciplinarity in nano scale research does not differ from other science and engineering research. Schummer, (2004) argues that nano scale research shows no special interdisciplinarity but rather multidisciplinarity consisting of different (unrelated) fields sharing only a “nano” prefix.

There are also different opinions on how to measure the interdisciplinary nature of basic research. Rafols and Meyer (2007) and Porter and Rafols (2009) argue that cognitive dimensions of research (e.g. citation and references) show a high and consistent degree of interdisciplinarity while social aspects (e.g. affiliation analysis) present a lesser and more erratic degree of interdisciplinarity. Rafols and Meyer (2007) suggest that bibliometric indicators based on citations and references can more accurately capture the generation of cross-disciplinary knowledge than tracking disciplinary affiliations. In particular, Porter and Chubin (1985) support the use of citations outside category as an indicator of interdisciplinary research activity. However, Schummer (2004) states that a co-author analysis can cover different aspects of interdisciplinarity than other methods.

This paper examines the interdisciplinary level of nano industrial sectors. We argue that the cognitive dimension is more important than the institutional (team) collaboration aspect. However, the cognitive dimension has more than one side. This paper explores nano industrial interdisciplinarity not only from the co-words aspect, but also from the citation aspect. Co-word analysis reveals the overlapping degree of nano sectors, while citation analysis discloses the core field of nano research. Institutional collaboration as an auxiliary means is also presented in explaining the feature of nano industrial interdisciplinarity. As to the nano field classification, different from using the journal classification (Meyer and Persson 1998) and nano title papers (Schummer 2004; Braun et al. 1997), we classify nano industrial areas through vocabulary mining, which we believe to provide a more accurate dimension of the analysis (see the next section).

2. Methodology

Based on Web of Science data, we have harvested nano-publications totalling 625,471 records from 8,700 of the most prestigious academic journals for the past 11 years (1998-2008). The database is constructed based on a lexical query searching and defining strategy developed by the Georgia Institute of Technology (see Porter et al. 2008). Through 16 different algorithms connected together, the search for nano scale scientific research provides a broad but not too excessively expansive collection of hits within the Web of Science database (see more details in Newman et al. 2009 and Huang et al. 2010). The nano publication data has been cleaned and noisy records have been excluded. For instance, records containing irrelevant keywords (e.g. nanoliter, nanometer and nano3) have been removed from our database.

Due to the fact that the publication database is built up from academic journals without the necessary industrial classifications, it is of importance to define industrial groups in order to carry on sectoral analysis in nanoscience.

The first step in our methodology is to select suitable vocabularies to mine. We are interested in defining the use of nanotechnology in the following five industrial sectors:

1. Chemistry & materials
2. Health, medicine & bionano
3. ICT
4. Energy
5. Aeronautics & automotive

Looking at the larger communities or knowledge networks (table 1. column 2) involved in research in these sectors we come up with the following selection (table 1. column 3):

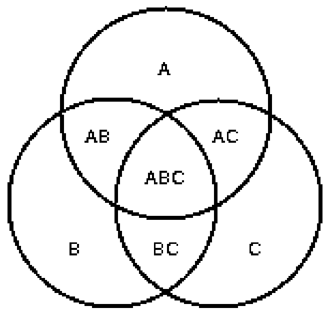
Table 1: Selected ontologies and combinations for studied industrial sectors

Sectors	Community	Ontology
1	Engineering Village (EI Compendex)	Compendex Thesaurus
2	Pubmed	MeSH (Medical Subject Headings)
3	IEEE	Inspec Thesaurus
4	ETDE	ETDE-INIS Joint Subject Thesaurus
5	NASA	NASA Thesaurus

In a two step procedure sectoral keyword sets were defined by mining the above vocabularies using a nano-prefixed term query. Similar to divisive clustering (a form of hierarchical clustering) a top-down approach was employed, where we draw a boundary at the second level. In practice this means that the thesauri are mined in two rounds, first a search for nano-prefixed terms is done in which the focus is on ”used for” terms (UF), related terms (RT) and narrower (NT) terms. Then, in a second round the thesauri are searched for the NT terms from the first round and the UF, RT and NT terms of this NT term are mined. An expansion can be made to include, through searching and subsequently mining for UF, RT and NT terms, of the RT terms from the first round. The resulting keyword sets contain same or similar keywords (with membership of multiple clusters) but also contain unique keywords (unique to the cluster). These characteristics can also be found in fuzzy clustering, where each keyword has a degree of belonging to two or several clusters, rather than belonging to only one cluster. Keywords on the virtual boundaries of a set may then belong to the set to a lesser degree than keywords which are in the “nucleus” of the set. These characteristics however imply that, if one is using single keywords to identify documents, there needs to be the ability to discern between individual keywords using their presumed value (degree of belonging – degree of membership) as an identifier. In the proposed methodology this is done by giving each keyword a simple weighting according to its frequency ratio (term density) throughout the clusters.

In the next step a frequency matrix is assembled in which this weighting value is assigned to each of the keywords. The keywords with the least weight, or least membership, are then the unique keywords defining a distinct sector, whilst all keywords with a higher weighting are keywords with multiple memberships defining cross-sectoral research. We set a threshold of a single membership (a weight of 0.1) to define two sub-sets of keywords. One sub-set (A, B, C) which is then an exclusive, and the other sub-set (AB, AC, BC, ABC) which is an intersection with further keyword sets:

Diagram1: A Venn diagram of 3 sets



Source: http://www.combinatorics.org.

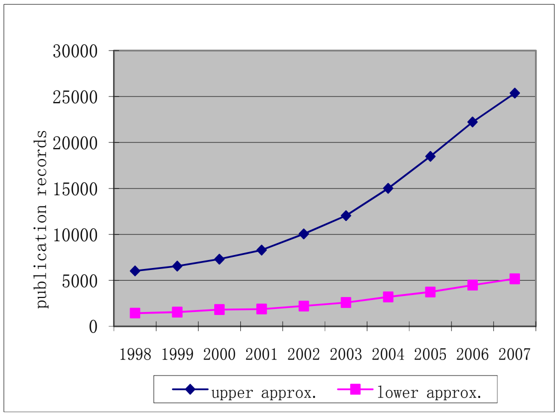
3. Integration between nano industries: Co-keyword analysis

Looking at nano sectors from a fuzzy-rough set theory angle, as mentioned before, it is possible to distinguish between the two above mentioned sub-sets, one being an upper, and one being a lower approximation of the sectoral keyword set (the approximation space). In other words, the upper approximation is the set of keywords with a general and integrative sectoral meaning, while the lower approximation is the set of keywords signifying sectoral specialization.

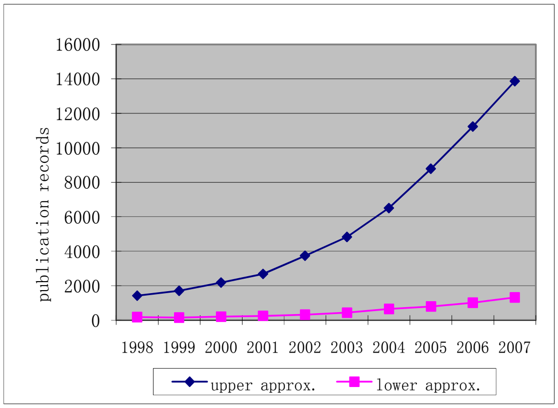
The set of figures 1-a to 1-e shows a division of the publication output in two approximations in the analyzed five sectors. Upper approximation publication records show the trend in publication output per sector of basic research which would be of possible interest to more than one sector. Lower approximation publication records show the trend in publication output per sector of basic research specifically of interest to that specific sector. One can see that the gap between sector-specific and cross-sectoral research is widening. Among all the five sectors, the two lines plotted for the *energy* sector are closest compared with those in other sectors. This presents a clear and fast growth of energy-specific nano-research diverging not to far from the more general research. For the remaining four sectors, the figures indicate that the general and integrative research grows faster than sector-specific research, at least from the perspective of publication records.

Figure 1: Comparison between upper and lower approximation in nano sectors

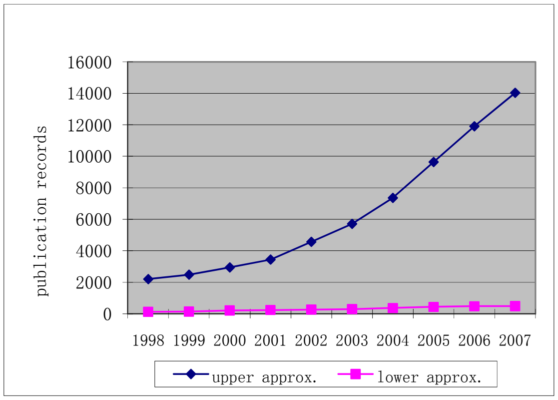
1-a Chemistry& materials



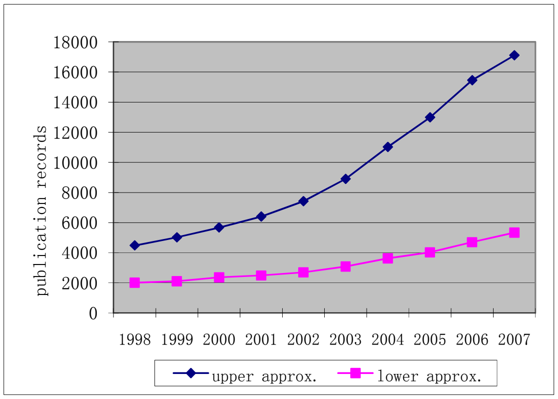
1-b Health, medicine & bionano



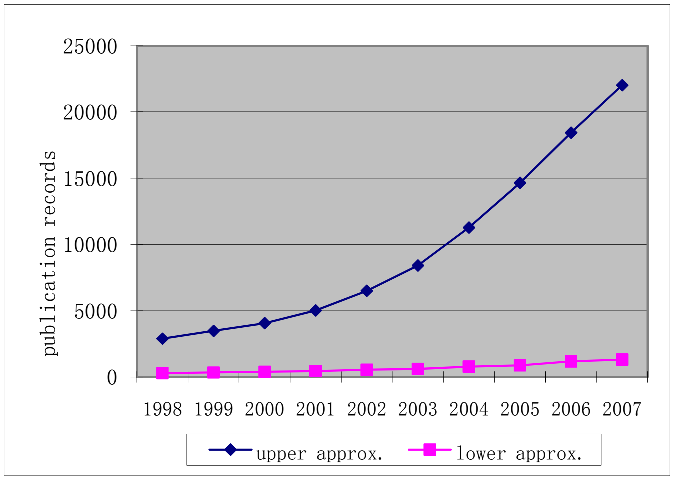
1-c ICT



1-d Energy

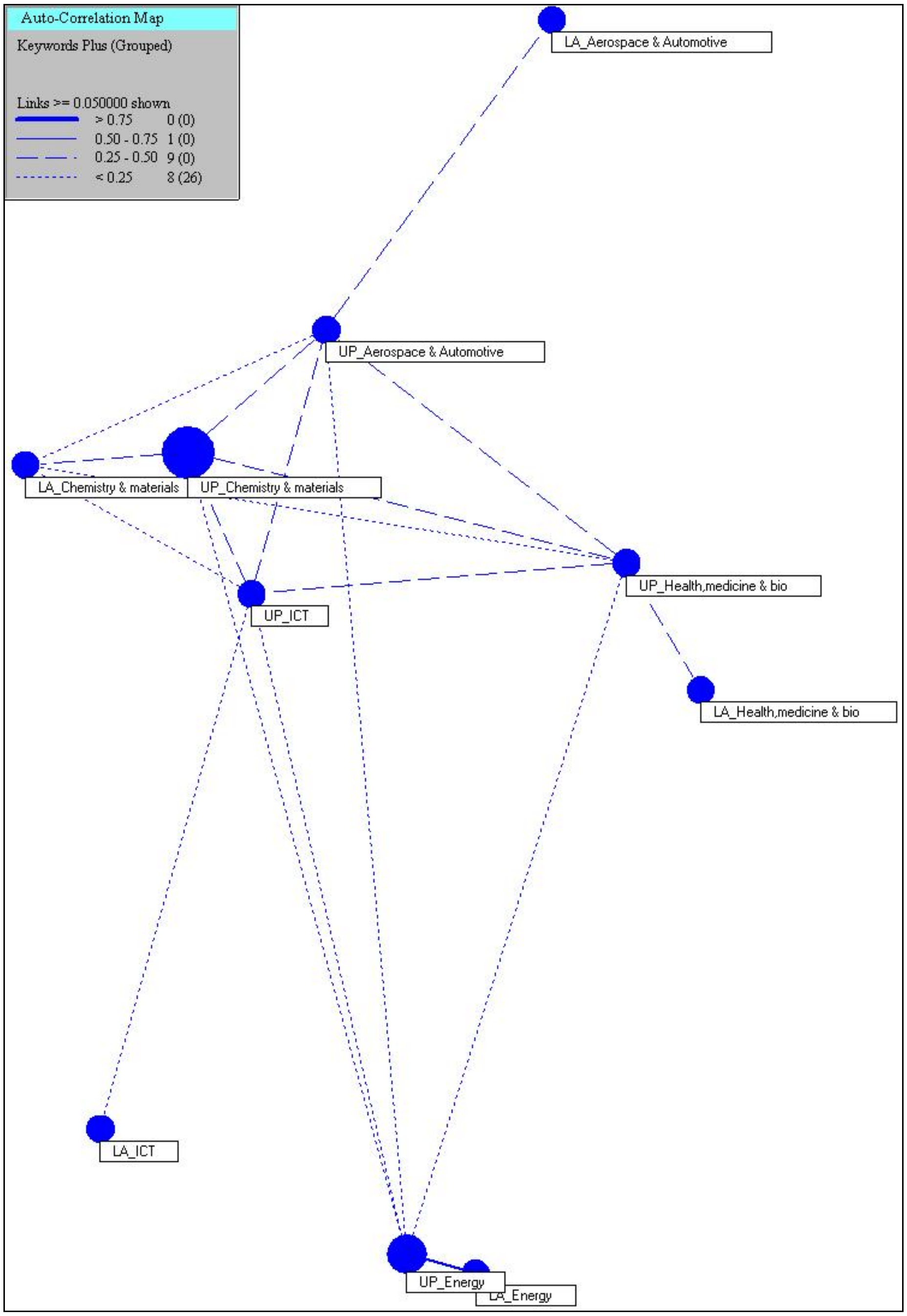


1-e Aeronautics & automotive



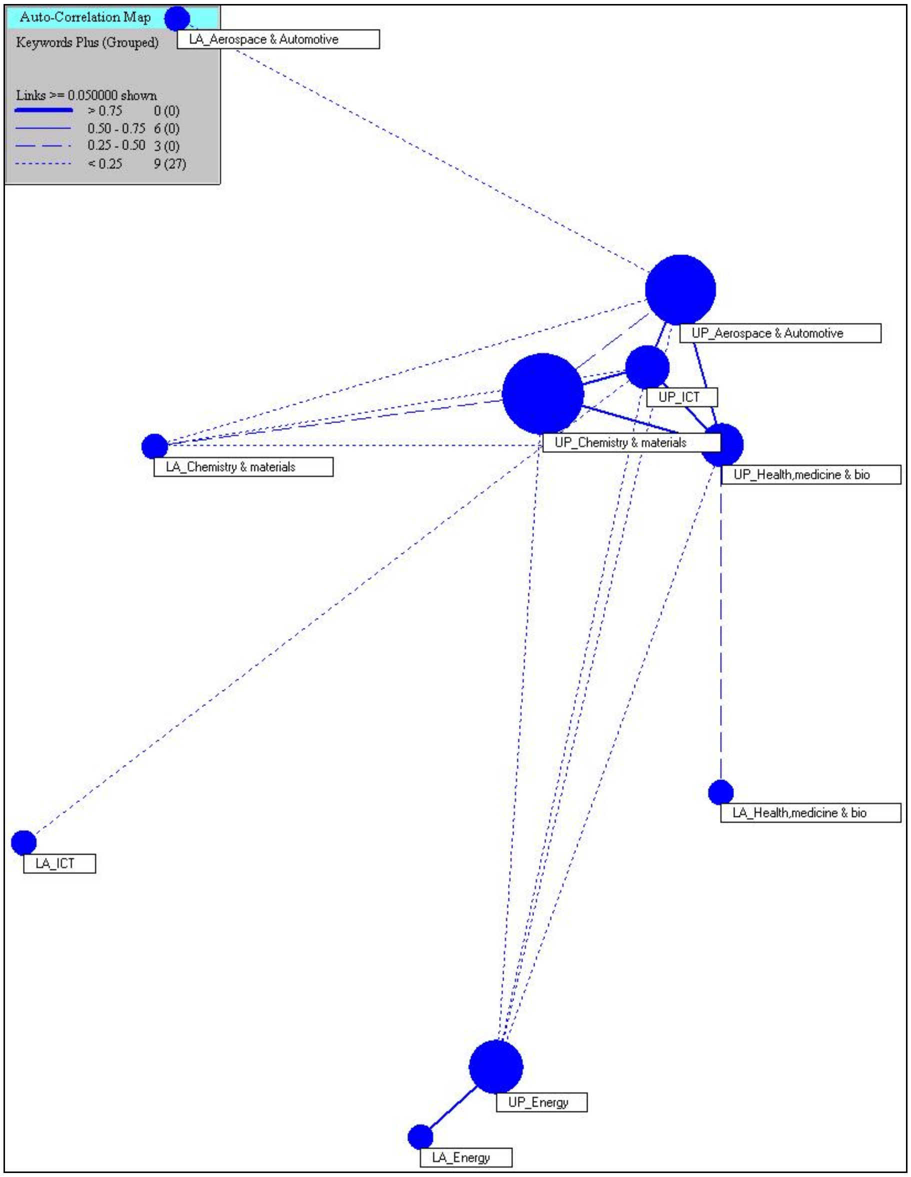
This section explores the interdisciplinary nature of nanotechnology research for the five sectors through co-word analysis. Based on the sectoral classification described in previous section, Figures 2 and 3 show the degree of overlap and integration among sectors in 1998 and 2007 respectively. In these figures, strength of overlap is shown by the transparency of the connecting lines. The thicker the line, the stronger the integration between sectors will be. Obviously, the upper (UP) and the lower approximations (LA) of each sector have a strong overlap, due to the fact that the latter is a sub-set of the former.

Figure 2: Interdisciplinarity among five sectors in 1988



Note: This is figure is based on the co-word analysis among sectors.

Figure 3: Interdisciplinarity among five sectors in 2007



Note: This is figure is based on the co-word analysis among sectors.

Figure 3 shows that, on one hand, at the lower approximation level, LA_*Chemistry & materials* is the only sector having with other four upper approximation groups, the rest four have connections with only their own upper level sectors. This presents the truth that lower approximation *Chemisty & material* shares common topics with the other four upper approximation sectors. On the other hand, at the upper approximation level, the *ICT* and *Health, medicine & bionan*o sector has the most interdisicplinarity, with three strong connections with other sectors. (This is based on the intensity of connections related to the size of publication pools. Therefore, though *Chemistry & material* shares more keywords with sectors, but due to the large amount of publication in *Chemistry & material*, the intensity of its connections is less strong.)

Comparing Figure 2 and Figure 3, one can see that the co-word overlap among the studied five sectors is increasing in the time period from 1998 to 2007, which indicates that the interdisciplinarity among these five nano sectors is getting stronger over time, in the cognitive sense. The use of the co-word method is superior, in our opinion, to the analysis of "nano-titled" papers as criticized by Schummer (2004), because the former examines publications from the cognitive point of view, i.e. looking at the content of the paper, while the latter deals only with papers selected on the basis of nano-prefixed titles.

The connections between these five industrial sectors also confirm that each sector can use a sectoral innovation system "…to build a technology-product matrix that links the products to a range of technologies" (Malerba 2004, pp. 18). The increasing links between sectors also show that in one sectoral system the technological diversification is getting stronger over time.

4. Interdisciplinary nature: Citations in nano-sectors

In bibliometrics, content analysis and citation analysis are both of importance. If we regard content analysis as the methodology examining cognitive communication from a quantitative aspect, then citation analysis is the type of method exploring the frequency and pattern of links between academic works or researchers. Following the co-word content analysis in previous section, this part of our paper examines the interdisciplinary nature of nanoscience based on the citation analysis.

General citation analysis based on *Journal Impact Factor* has been often adopted as an approach measuring research quality, with an indication that the more cited the better quality the publication is. However, we argue that the citation among industrial sectors symbolizes more links between sectors, namely, that the more cited the core role this sector plays, though it might also indicate the quality level and reputation of the works or scholars in this sector.

4.1 Publication quality- citations in five sectors

Table 2 gives us a wealth of information on the total amount of publications per sector, divided by the two earlier separated sets: cross-sectoral articles (Upper approximation) and sector specific articles (Lower approximation). It also presents us with stratified citation data where we can see the amount and ratio of articles cited more than 100, 200 and 500 times, as well as the average times cited per sector and sub-set.

Table 2: Citation ratios in five sectors (1998-2007)

	1	2	3	4	5
	Upper approximation				
sector	Chemistry & materials	Aeronautics & automotive	Energy	ICT	Health, medicine & bio
records	131366	96763	94484	64269	56933
Cited Sum	1472332	1096658	1053434	786156	681627
Cited Average	11	11	11	12	12
Cited>=100 (sum)	1462	1188	1031	884	792
Cited>=100 (ratio)	1.11%	1.23%	1.09%	1.38%	1.39%
Cited>=200 (sum)	328	296	259	227	198
Cited>=200 (ratio)	0.25%	0.31%	0.27%	0.35%	0.35%
Cited>=500 (sum)	46	42	49	39	34
Cited>=500 (ratio)	0.04%	0.04%	0.05%	0.06%	0.06%
	Lower approximation				
sector	Energy	Chemistry & materials	Aerospace & Automotive	Health, medicine & bio	ICT
records	32441	28022	6809	5308	2995
Cited Sum	386139	334892	80888	64229	41540
Cited Average	12	12	12	12	14
Cited>=100 (sum)	358	332	99	59	41
Cited>=100 (ratio)	1.10%	1.18%	1.45%	1.11%	1.37%
Cited>=200 (sum)	89	72	23	9	19

Cited>=200 (ratio)	0.27%	0.26%	0.34%	0.17%	0.63%
Cited>=500 (sum)	12	12	0	3	3
Cited>=500 (ratio)	0.04%	0.04%	0.00%	0.06%	0.10%

Note: "Cited>=100 (sum)" is the number of publications cited more than 100 times. "Cited>=100 (ratio)" is the percentage of the Cited>=100 (sum) out of cited publication numbers. The same rule applies to Cited>=200 and Cited>=500.

What is also apparent from the above Table 2 is that *Health, medicine & bionano* and *ICT* are the most highly cited sectors. Although *Health, medicine & bionano* is quite consistent, for *ICT* there is a jump in citation numbers between the more cross-sectoral and sector specific articles. We should nevertheless acknowledge the possibility of disciplinary differences in citation practices. It is also interesting to see that across the five sectors analysed there is little divergence in average citation numbers and that on average more industry specific, or industry focussed, publications have a slightly higher ratio of citations. This latter characteristic is counter-intuitive. One would think that cross-disciplinary/sectoral articles would get higher citation numbers due to their wide applicability. However what we see from the table is that the opposite is true.

4.2 Cross-sectoral citations

Porter and Chubin (1985) state that *citations outside category* is an important indicator of measuring interdisciplinary level of research activities. Cross-sectoral citations present interaction between sectors and reveal the core field of research for others.

Table 3 provides the cross-cited information among the five sectors. It shows that, without doubting, each of the five sectors cited publications from their own sectors most. Following that, *Aeronautics & automotive* and *Chemistry & materials* are the two most cited sectors. For instance, in the total publications cited by *Energy*, 15% is from *Aeronautics & automotive* and 18% is from *Chemistry & materials*; in the total publications cited by *Health, medicine & bionano*, 23% is from *Aeronautics & automotive* and 21% is from *Chemistry & materials*; in the total publications cited by *ICT*, 20% is from *Aeronautics & automotive* and 24% is from *Chemistry & materials*.

Table 3: Cited publications cross five sectors (1998-2007)

		1	2	3	4	5	total
		93943	**58601**	**47606**	**42345**	**27923**	
		Aeronautics & automotive	**Chemistry & materials**	**Health, medicine & bio**	**ICT**	**Energy**	
Aeronautics	Sum	1096658	682131	574808	495410	344047	
	average*	11	11	12	12	11	
	percentage**	34%	21%	18%	16%	11%	100%
Chemistry	sum	682131	1472332	522740	601256	407266	
	average	11	11	12	12	12	
	percentage	19%	40%	14%	16%	11%	100%
Energy	sum	344047	407266	250756	227207	1053434	
	average	11	12	12	13	11	
	percentage	15%	18%	11%	10%	46%	100%
Health	sum	574808	522740	681627	417757	250756	
	average	12	12	12	12	12	
	percentage	23%	21%	28%	17%	10%	100%
ICT	sum	495410	601256	417757	786156	227207	
	average	12	12	12	12	13	
	percentage	20%	24%	17%	31%	9%	100%

Note: (1)*average is the cited times divided by the total publication records in the cited sector.

(2) **percentage is calculated by the cited times in certain sector divided by the number of all cited papers.

(3) All the sectors are up-approximation sectors.

Given that citations have a time lag after publication, there is not much sense comparing early and later years. Therefore this table combine all the years together rather than presenting 1998 and 2007 separately.

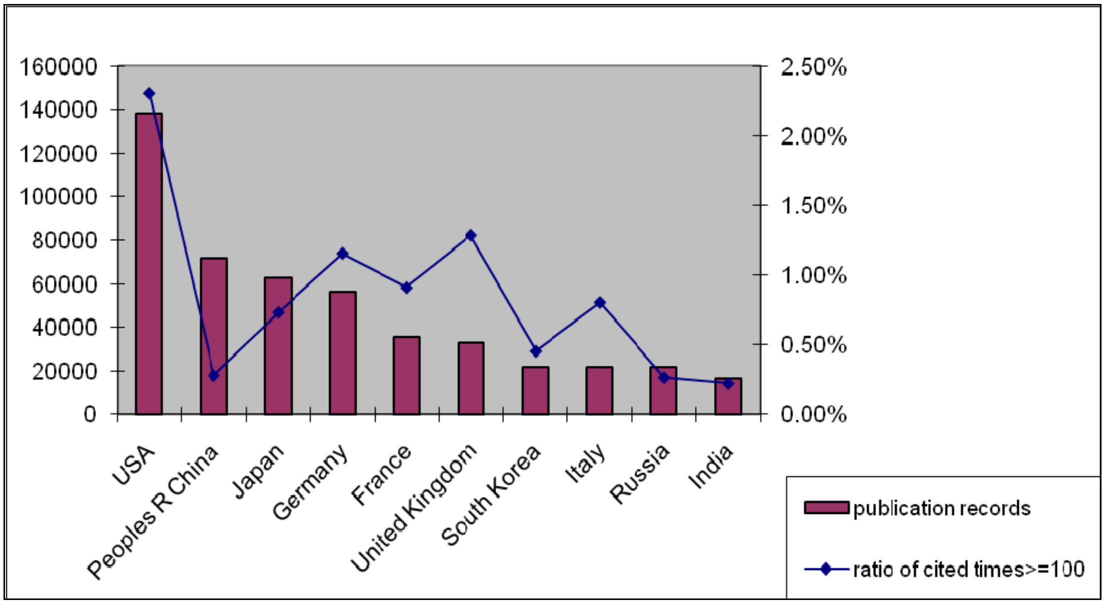
It is well recognized that "hard pure" (Becher and Trowler 2001) research fields (e.g. mathematics or statistics) are more likely to be cited most by other fields (Porter and Chubin 1985). The five studied nano-sectors in this paper are all industrial sectors, hence it excludes the case of apparent "hard pure" citations in specific fields. Therefore, we can draw that conclusion form Table 2 that *Chemistry & materials* and *Aeronautics & automotive* is the relatively core research field with successful nanoscience applications. Other three sectors have been learning actively from *Chemistry & materials* and *Aerounautics & automotive*.

4.3 Geographic concentrations of citations

The following figure provides information on the main geographic locations of cited publications. USA has the highest citation ratio and the most publications. The United Kingdom has the second highest citation ratio, though its publication number ranks at sixth place worldwide. Contrary to this comparison, China and Japan perform well in terms of total publication records, however their citation ratios are relatively low compared with the aforementioned publication numbers.

If citation is an indication of research quality and basic research reputation, it becomes apparent that the European countries analysed above (Germany, France, United Kingdom, and Italy) are clearly performing well, as well as the USA, in terms of citation of the total nano science output. What is interesting to see is that irrespective of the total amount of publications, citation scores for the Anglophone countries (USA & UK) are high. Whether this is a result of the fact that most high impact journals are also from these countries is not clear from our analysis, but this fact could have an impact. Nevertheless, Germany, France, Italy and Japan are also scoring high in terms of citations, so a language bias can be safely ruled out.

Figure 4: Publication records and citation ratios in top countries



Note: Citation ratio is the proportion of publications cited >=100 times in the total cited publications.

5. Institutional cooperation

At the social level, inter-organizational networks have important contribution in the integrative innovation process of nano industries. As Schummer (2004) argues, co-words and citation analysis reveals the interdisciplinarity in terms of information, while co-author analysis focus on the social aspect of interdisciplinarity. Considering the fact of that author names are getting more and more mixed along with the growth of publication records. In particular, many different Chinese (or Korean) authors sharing the same names, which makes the co-author analysis less pronounced. Therefore, this paper carries out cooperation analysis from an institutional viewpoint instead of using co-authorships.

The above analysis shows stronger connections between sectors over time from the content and citation point of view. One may wonder what the institutional features are behind this fact. As Porter et al (2007) indicates, institutional parameters which nurture interdisciplinarity are worthwhile analyzing. In the nano publication pool, there are four types of affiliations, namely, academic, government, corporate and hospital[1]. Table 4 presents the features of institutional collaboration in 1998 and 2007.

Table 4: Institutional cooperation in 1998 and 2007

1998				
	1	2	3	4
	Academic	**Government/NGO**	**Corporate**	**Hospital**
Academic	1	0.10	0.05	0.01
Government/NGO	0.75	1	0.05	0.01
Corporate	0.55	0.07	1	0.01
Hospital	0.72	0.09	0.05	1
2007				
	1	2	3	4
	Academic	**Government/NGO**	**Corporate**	**Hospital**
Academic	1	0.13	0.05	0.01
Government/NGO	0.84	1	0.05	0.01
Corporate	0.73	0.13	1	0.01
Hospital	0.82	0.13	0.05	1

The cooperation links between *Academic* and the rest of organization types have all increased most over time. Following that, the cooperation between *Government* and others have increased mildly. However, the cooperation between *hospital* and *corporate* stays the same. The table shows that *Academic* and *Government/NGO* are the two most active organizations which have improved their cooperation with all the others (see column 1 and column 2).

From the above analysis, it shows that the institutions of *academic* and *government* seem to play very important roles in the innovation process of diverse nano technologies.

[1] Though hospitals are often attached to universities or research institute, they are private in many countries. Therefore we have hospital as one separate category instead of being incorporated into academic.

6. Conclusions

Based on our nano science database harvested from the Web of Science, this paper investigated the innovation patterns in nano industries from an interdisciplinary perspective. We employ recognized bibliometric techniques as well as set theory mathematics to define five nano industrial sectors, *Chemistry & materials*, Health, m*edicine & bionano*, *ICT*, *Energy* and *Aeronautics & automotive*, which are subsequently analyzed. The analysis covers two sets on a sectoral scale: one set has specific keywords which are of direct interest to the industrial sector, the other has general keywords with varying degrees of overlap with other sectoral sets.

Our analysis involves both cognitive and institutional dimensions. Furthermore, the cognitive dimension covers not only the co-word aspect, but also the citation aspect. Co-word analysis reveals the overlapping degree of research within nano industrial sectors, while citation analysis discloses the core field of nano research.

The results of this paper show that, regarding the co-word analysis, the lower approximation level *Chemistry & materials* seems to share a tremendous amount of common knowledge with the other four upper level sectors, but the upper approximation levels of Health, m*edicine & bionano* and *ICT* have a higher overlap with others. With respect to the cross-citation aspect, *Chemistry & materials* and *Aeronautics & automotive* are the core research fields and they have very important reference values for the other sectors. Our analysis also shows that citations from outside categories share a fairly high proportion in the whole reference pool, which indicates a high rate of external learning.

Institutional cooperation analysis indicates that among the four studied organizational groups (*Academic*, *Government*, *Corporate* and *Hospital*), the cooperation links between *Academic* and the rest of the organizational types have increased most over time. Following that, the cooperation between *Government* and others has increased only mildly. However, the cooperation between *hospital* and *corporate* remains static.

Based on our analysis, we can draw the following conclusions: First, technologies involved in one industrial sector become more diverse over time. The connections between nano industries get stronger and the general trend of interdisciplinarity in the studied nano sectors is converging in the long run, although the degree of this convergence depends greatly on the indicators one chooses.

Secondly, the interaction pattern in industries embodies the stage of knowledge development and transfer as well. If the knowledge is more tacit and constantly changing, there will be more informal means of knowledge transfer, e.g. oral communication or personnel mobility. However, "the more the knowledge is standardized, codified, simplified and independent, the more relevant are formal means of knowledge communication, such as publications, licenses, patents, and so on" (Breschi and Malerba 1997). From the above industrial publication, citation and cooperation analysis, one can also see that nano technology (in all the five studied sectors) gets more mature and standardized, and as such more codified.

Thirdly, the results of our analysis also indicate that more support should be given to the most cited sectors, e.g. *Health, medicine & bionano* and *ICT*, which seem to be the basis for other areas in a general sense, and for *Chemistry & materials* and *Aeronautics & automotive* which are the core fields in the five studied areas.

Above all, creating more communication platforms between industrial sectors is of importance to facilitate the collaboration and integration between different nano industrial sectors.

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