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# Research trends in nanotechnology studies across geo-economic areas

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**ABSTRACT:** The purpose of this paper is to analyze the current temporal and spatial research trajectories in nanoscience and nanotechnology studies in order to display the worldwide patterns of research fields across main economic players. The results show the leadership of Europe and North America in nanotechnology research, although the role of China has been growing over time. Current nanotechnology studies have been growing in chemistry and medicine because of applications of nanomaterials mainly in Chemical Engineering, Biochemistry, Genetics and Molecular Biology. Results also show a relative higher scientific performance in nanotechnology research production by South Korea in comparison with Japan and other geo-economic areas. This research can provide vital findings to support research and innovation policies aimed at improving the development of this technological system for modern patterns of economic growth.

**KEYWORDS:** Nanoscience, Nanotechnology, Technological Trajectories, Research Trends, Data Mining, Comparative Innovation Systems, Technological System

**JEL-CODES:** L6; O3; Q57

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## 1. INTRODUCTION

Modern patterns of economic growth are also driven by nanotechnologies and nanoscience which represent a new “technological system” (Freeman and Soete, 1987, p. 67). Nanoscience studies are flourishing in several countries and scientists tend, more and more, to publish on some critical research topics such as recently invented nanomaterials, new techniques that are suitable to study and characterize them, preparation techniques and substances used to produce nanomaterials and nanostructured objects, properties and technological uses of nanostructured materials and so on (*cf.* Islam and Miyazaki, 2010; Bainbridge and Roco, 2006). The importance of nanotechnologies and nanoscience has begun to go beyond the bare entourage of laboratories and research centres and is nowadays well present everywhere industrial innovation takes place (Goddard III *et al.*, 2007). In fact, nanotechnological innovations are critical in several industries such as microelectronics, chemistry, public health, environment, etc. (*see* Bainbridge and Roco, 2006; Pilkington *et al.*, 2009; Tegart, 2009; Glenn, 2006; van Merkerk and van Lente, 2005).

The spreading of nanotechnology in hard sciences and in technological applications has also caused the insurgence of great interest towards their study by economics of science and innovation (*cf.* Bozeman *et al.*, 2007). In fact, there is a vital interest to analyze the technological trajectories of nanotechnology and the specificity of countries in nanoscience production and its application in order to forecast research trends and future effects onto industrial dynamics across sectors and industries (*cf.* Salerno *et al.*, 2008; Bainbridge and Roco, 2006; de Miranda Santo *et al.*, 2006).

The purpose of this paper is to analyze the current technological trajectories in nanosciences and nanotechnologies across worldwide economic players. In particular, the main research questions addressed are:

- Which are the current driving research fields where nanotechnologies have been applied?
- Which is the behaviour of leading geo-economic areas in the production of nanoscience and nanotechnology knowledge?
- Which is the intensity of scientific collaborations across leading geo-economic players?

This research, performed exploiting the Scopus dataset (2010), will analyze the codified production in this vital “technological system” to show how different geo-economic regions (such as the North America and Europe) have acted and reacted towards nanotechnology studies, and how they have been behaving over time in the scientific knowledge production and international collaboration in Nanoscience and Nanotechnologies (NSTs). This research can provide main findings in order to understand the current worldwide research trends in NSTs. This is important to support innovation policies aimed at improving the development of such converging technologies able to support modern patterns of economic growth.

This paper presents in section 2 a theoretical framework about nanotechnologies and nanosciences; section 3 describes the methodology of research, whereas section 4 analyzes the results and section 5 discusses lessons learned and some concluding remarks.

## 2. THEORETICAL BACKGROUND ON NANOTECHNOLOGY STUDIES

“Nanoscience is the result of interdisciplinary cooperation between physics, chemistry, biotechnology, material sciences and engineering towards studying assemblies of atoms and molecules” (Renn and Roco, 2006, p. 154)<sup>1</sup>.

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<sup>1</sup> *Cf.* also Roco, 2007, pp. 3.1-3.26.

The “birth certificate” of NSTs, at least from the conceptual point of view, is considered the renowned speech given at an American Physical Society meeting at California Institute of Technology by Richard P. Feynman (1960), where the 1965 Nobel Prize Laureate uttered the famous sentence “There is plenty of room at the bottom” talking about the opportunities for science and technology given by the vast expansion of scientific and technological research towards the nanometric dimensional range and describing molecular machines built with atomic precision. The first use of the word “nano-technology” instead has to be assigned to Taniguchi (1974) of Tokyo Science University, who used it in an article on ion-sputtering machining.

Since then, the spreading and growth of NSTs has been marked by inventions and findings in terms of new nanostructured materials, investigation and characterization techniques, and new nano-objects. By the operational point of view, one of the most common opinion is that NSTs did originate in 1981 with the creation of Scanning Tunnelling Microscope (STM) in the IBM laboratories in Zurich, by 1986 Nobel Prizes Laureates for Physics Gerd K. Binnig and Heinrich Rohrer (Bonaccorsi and Thoma 2007). From the point of view of nanostructured materials 1985 marks the discovery of Buckyball (Buckminsterfullerene) by Kroto and Smalley (the discovery will gain them the Nobel Prize in Chemistry in 1996, see Kroto *et al.*, 1985); 1990 the discovery of Silica mesoporous materials by Yanagisawa and co-workers at Waseda University in Tokio (Yanagisawa *et al.*, 1990); 1991 the discovery of Carbon nanotubes by Iijima (1991) at NEC Corp. By the point of view of new nanostructured objects, it is remarkable the work performed by Eigler and Schweizer (1990) who did spell the IBM logo in individual atoms on a nickel surface. Several scientific journals having the stem “nano” on their title are published nowadays.

NSTs represent mostly an approach to science, technology and innovation rather than a specific sector by itself. For instance,

the website of the American National Nanotechnology Initiative<sup>2</sup> states<sup>3</sup>:

Nanoscience involves research to discover new behaviours and properties of materials with dimensions at the nanoscale which ranges roughly from 1 to 100 nanometres (nm). Nanotechnology is the way discoveries made at the nanoscale is put to work. Nanotechnology is more than throwing together a batch of nanoscale materials — it requires the ability to manipulate and control those materials in a useful way.

Nanotechnology is the understanding and control of matter at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications. Encompassing nanoscale science, engineering, and technology, nanotechnology involves imaging, measuring, modelling, and manipulating matter at this length scale [...] Unusual physical, chemical, and biological properties can emerge in materials at the nanoscale. These properties may differ in important ways from the properties of bulk materials and single atoms or molecules.

By one side the definition discriminates between science and technology, which is sometimes hard to tell. But on the other side, it describes precisely and briefly the fundamental characters of NSTs: they act in a well defined dimensional field and this is substantial and cannot be disregarded; purpose is discovering new behaviours and properties distinctive of materials when nanostructured. From this point onwards, technologies have the purpose of transforming the new knowledge in innovation.

As we can define NSTs as an approach towards matter, when we discuss the transfer of nanoscience into technological innovation, as far as the “transversal” character of NSTs has been defined, it is clear that we cannot talk about “application sectors” of NSTs.

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<sup>2</sup> See: [http://www.nano.gov/Nanotechnology\\_BigThingsfromaTinyWorldspread.pdf](http://www.nano.gov/Nanotechnology_BigThingsfromaTinyWorldspread.pdf), accessed May 2010; <http://www.nano.gov/html/facts/whatIsNano.html>; accessed June 2010.

<sup>3</sup> Cf. also Siegel *et al.*, 1999.

This, not because nanotechnologies cannot be applied to industrial innovation and to the production of goods, but, on the contrary, because the list of sectors is virtually endless.

The technological application of NSTs has been first of all in niche industries, mostly knowledge-intensive and with high-added-value products, such as the production of catalysts for industrial production (*cf.* Zecchina *et al.*, 2007; Evangelisti *et al.*, 2007) or biomaterials produced for bone substitution inside the human body (*cf.* Bertinetti *et al.*, 2006; Celotti *et al.*, 2006). In these cases, the distance existing between basic/purpose-free research and technological innovation is almost not existing, or very narrow, and the high added value of goods justifies the economic engagement of the scientific research.

Other edge industries where the use of nanotechnologies is established are those of biotechnologies and electronics. In this last case the downscaling of circuitry – until the present limit of 45 nm (nanometers) – has mostly benefited of the extreme frontier of manipulation technologies in order to reach a higher miniaturization.

NSTs are not only transversal to possible industrial applications, but also to scientific sectors: *e.g.* material sciences, chemical and physical sciences, and material engineering. Different traditional scientific fields have in general a different approach towards NSTs, as well described by Balzani (2005) who gives his own definition of sciences and technologies, and underlines the different approaches adopted towards NSTs by different categories of scientists. The typical approach of physicists and engineers is the so-called *top-down* approach, where the matter is manipulated instrumentally – *e.g.* with the techniques of photolithography – in order to obtain the desired results: in this way the dimensional barrier of 100 nanometers has been a hard one to overcome.

The typical approach of chemists is exactly reverse to the previous one: a *bottom-up* approach where objects lying in the molecular dimensional domain – thus around

and slightly below the nanometer – can be used as “bricks” to build nanostructured objects with bigger dimensions, such as the molecular computers with high scientific and technological content in the quest for an innovating application.

Nanotechnologies are nowadays fully inserted in the paths of “creative destructions” generated by technical knowledge in industries (Bozeman *et al.*, 2007). NSTs are at the convergence of several scientific and technological fields and affect the organizational behaviour of both entrant firms and incumbents in several sectors (Bainbridge and Roco, 2006). Moreover, university spinouts in NSTs are gaining importance and are playing a critical role for regional development (Libaers *et al.*, 2006). NSTs are also in a cutting-edge position in order to enhance new systems for environmental control and remediation, though some envisage dangers from their use (Rickerby and Morrison, 2007).

Scientometrics studies are effective approaches to analyze the emergence and development of research fields in nanotechnology (Braun *et al.*, 1997). Leydesdorff and Zhou (2007), basing their work on Journal Citation Report data; “nano” journals have more complex content than other journals – from the point of view of citations – and their position is at the interface between physics and chemistry. In fact, Leydesdorff (2008) shows the growing interdisciplinary effects of NSTs.

Kostoff *et al.* (2006; 2007; 2007a) describe an overview on the NSTs literature. These works show the continuous evolution and growth in NSTs, also driven by Asian countries.

It is then obvious from this theoretical background that a deep scientific analysis of research trends in the scientific production of NSTs across leading worldwide players is an important topic to be developed in order to understand the current technological trajectories that may support future spatial patterns of economic growth.

### 3. METHODOLOGY OF RESEARCH

Salerno *et al.* (2008) argue that: “Bibliometric analysis of publications [...] can help have a synthetic picture of the best players at a worldwide level, their lines of inquiries and their relationships, that is, they could help to cope with the extremely fragmented knowledge, actors and applications involved in the evolution of the field” (p. 1220). This paper uses Scopus database (2010). “Scopus is the largest abstract and citation database of peer-reviewed literature and quality web sources with smart tools to track, analyze and visualize research. It’s designed to find the information scientists need [...] Scopus provides superior support of the literature research process” (Scopus, 2010)<sup>4</sup>.

Scopus has been preferred to other analogous web-databases because:

- It encompasses a wider set of data: “With over 18,000 titles from more than 5,000 publishers, Scopus offers researchers a quick, easy and comprehensive resource to support their research needs in the scientific, technical, medical and social science fields and, more recently, also in the arts and humanities”<sup>5</sup>.
- It has the broadest available coverage, with more than half of the content originating from Europe, Latin America and the Asia Pacific region<sup>6</sup>.
- It has a wide set of data retrieval instruments, useful in performing Data Mining.
- It exploits a system of classification of titles under categories: “Titles in Scopus are classified under four broad subject clusters (Life Sciences, Physical Sciences, Health Sciences and Social Sciences & Humanities) which are further divided

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<sup>4</sup> <http://info.scopus.com/about/> (accessed 11 June 2010); See also <http://info.scopus.com/why-scopus/academia/> (accessed June 18<sup>th</sup>, 2010).

<sup>5</sup> <http://info.scopus.com/scopus-in-detail/content-coverage-guide/> (accessed June 18<sup>th</sup>, 2010).

<sup>6</sup> <http://info.scopus.com/scopus-in-detail/facts/> (accessed July 1<sup>st</sup>, 2010).

into 27 major subject areas and 300 minor subject areas. Titles may belong to more than one subject area”<sup>7</sup>.

Data mining from Scopus (2010) was performed using the following methodology:

- a) the search of “nano\*”<sup>8</sup> on “Article Title, Abstract, Keyword” is made;
- b) on the selected records a further refinement is performed using the “Refine results” frame, selecting only those records containing one or more of the following keywords: “Nanostructured materials”, “Nanotechnology” or “Nanostructures”.

In particular, Data Mining is performed on:

- Time Horizon from 1996 to 2008 in order to analyze the temporal research trends. Within the range 1996-2008 we have the opportunity to retrieve all information analyzed, whereas this is not possible for year before 1996 (when Scopus starts gathering full data) and after the 2008 (as Data Mining was performed in January 2010).
- Key geo-economic areas: selected areas have been USA and Canada, South Korea, Japan, China and Europe<sup>9</sup>. These geo-economic and politic areas are the main worldwide players in the production of nanotechnology and nanoscience studies.

After that quantitative data have been retrieved, we have main information about several characteristics of scientific products. In particular we exploited the *affiliations* of

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<sup>7</sup> <http://info.scopus.com/scopus-in-detail/content-coverage-guide/journalclassification/> (accessed June 18<sup>th</sup>, 2010).

<sup>8</sup> “\*” is the usual dummy meaning “any series of character after the ones written”

<sup>9</sup> In “Europe” the selected countries are: Albania, Austria, Belarus, Belgium, Bosnia, Bulgaria, Croatia, Czech Republic, Estonia, Finland, France, Germany, Greece, Holland, Hungary, Ireland, Italy, Latvia, Lithuania, Macedonia, Moldova, The Netherlands, Norway, Poland, Portugal, Romania, Russia, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, and United Kingdom.



authors (*i.e.* main research institutions and/or labs where the research is carried out by scholars) and the *subject areas*<sup>10</sup> of nanoscience and nanotechnology studies published on leading scientific journals. Our samples are based on the 149 324 scientific products (*e.g.* Articles, proceedings, etc.) on nanotechnology studies with their affiliations (about 96% of main research centres operating in NSTs) retrieved as above described per countries and years. As papers concerning the nanotechnology studies are published on journals that are classified per 28 subject areas<sup>10</sup>, the 149,324 scientific products have almost 400,000 occurrences of subject areas. In general, the number of occurrences of subject areas by journals is greater than the total number of scientific products (*i.e.* papers)<sup>11</sup>. The occurrences of articles represent a view of subject areas in nanotechnology studies and how much attention they have received in the scientific literature.

The vast sample of papers classified by Scopus in main subject areas has been aggregated in five “Macro Subject Areas”: “Material Science”, “Chemistry and Medicine”, “Physics and Earth Sciences”, “Engineering”; all marginal areas of nanotechnology studies (less than 5% of the sample) have been included under the category “Others” (“Information and Mathematics Sciences”, “Social and Economic Sciences”, “Energy”, “Environmental Science”). Table 1A and 2A

<sup>10</sup> Scopus classifies journals in major subject areas, such as “Energy”, “Chemistry”, “Engineering”, etc. Journals can be allocated to multiple subject areas as appropriate to their scope. We use all subject areas containing papers on nanotechnology studies. Interestingly, the average number of subject areas that journals in the “Energy” papers belong to (2.09) is higher than the average value of all science (1.37), indicating that they exhibit a strong degree of interdisciplinarity.

<sup>11</sup> For instance a paper about the nanotechnology published on the journal *Scientometrics*, is one paper with 3 subject areas, since *Scientometrics* is classified with three subject areas (computer science applications, social sciences and library and information sciences).

in Appendix show the content of subject areas per each Macro Subject Areas (in short, macro areas). This aggregation has been important to show the temporal and spatial pattern of nanotechnology research trends across countries. The more detailed analysis per keywords has not been considered first of all because of the high number of generic keywords like “Synthesis”, “Chemistry”, “Priority journal”, “Crystallization”, “Methodology” etc. Moreover single keywords do not refer necessarily to a single research area, making such an analysis less meaningful. Also the categorization of research domains in “nanomaterials” and “nanoelectronics” has not been considered because of their inner overlaps: nanomaterials are heavily applied in nanoelectronics; therefore considering this categorization is not fruitful for investigating the real nanotechnology research trajectories and could bring to ambiguous results and misleading research trends. *Vice versa*, the aggregate sets applied in this research provide more accurate and robust results about the temporal and spatial research trends.

Another main analysis performed is that on the scientific cooperation in nanotechnology production across geo-economic areas. We have considered in each geographical area, for its scientific output, the foreign affiliations in nanotechnology studies in order to see the mutual cooperation for nano scientific research fields.

The main limit imposed by Scopus search engine is the maximum of 160 items (the most represented ones) for each data mining. Other limits could be the fact that NSTs are not present as an autonomous subject area in Scopus (limit overcome with our Data Mining) and not all papers /proceedings in nanotechnology studies are captured and included in Scopus dataset. Nevertheless this is also a weakness point for other web-based data collections. The information analysis of our samples is carried out by statistical and graphs analysis considering some critical research fields and geo-economic areas in order to show driving research trends in nanotechnology studies.

#### 4. EMPIRICAL ANALYSIS

This paper analyzes five main geo-economic areas in the production of nanotechnology, based on research centres and their scientific output present into Scopus (2010). For what about the structure of domestic research centres, their aggregate number has been calculated assigning the respective geo-economic area (of the primary physical base) to all occurrences of affiliations present in our databases producing at least a scientific product in nanotechnologies. The highest number of research labs in nanotechnology is in Europe and North America (*i.e.* USA and Canada) that have a steady trend over 1996-2008 period (Fig. 1). Europe and North America have in 2008 about 150 research centres operating in nanotechnology fields. Japan has a lower number of research centres if compared with previously described leading geo-economic areas, with roughly 100 units, with a stable cumulative temporal number in the range 107-117. China and South Korea are the two geo-economic areas where the number of nanotechnology research centres has been increasing, reducing in 2008 the high gap presents in 1996 in comparison with the level of Europe and North America<sup>12</sup>: in particular, China has more than 130 nanotechnology research centres operating in 2008 (Table 3A in Appendix shows the cumulative number of these research centres over 1996-2008 across geo-economic areas, and their scientific outputs in the last 15 years).

Figures 2-6 show the main research fields of nanoscience studies from 1996 to 2008 across geo-economic areas. As the absolute numbers of scientific products across geo-economic areas are not suitable values for reliable spatial and temporal comparisons (as research trends are similar), we apply percent values to analyze the mutual temporal dynamics within research fields in NSTs. These trends show some common patterns: although the nanotechnology studies in material science have un higher scientific

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<sup>12</sup> Cf. de Miranda Santo *et al.* (2006) pp. 1022ff.

production in comparison with other macro subject areas (see table 1A and 2A), the internal dynamics among macro subject areas shows mainly a relative reduction over time and space of studies in nanomaterial sciences (decreasing returns to production), whereas the studies of nanoscience applied in Chemistry and Medicine have been increasing<sup>13</sup>. In addition, the highest relative increase of nanoscience studies in Chemistry and Medicine, measured by coefficients of regression lines, is in China ( $\beta=2.2$ ) and South Korea ( $\beta=1.95$ ), whereas the lowest magnitude is in Japan ( $\beta=1.4$ ). These results indicate that some nanotechnology research domains which have generated main inventions of several nanomaterials are mature research fields, whereas nowadays studies of nanotechnology in Chemistry and Medicine have been growing because modern research centres focus their scientific research on critical innovation in more applied sectors of NSTs. This means that some nanotechnology trajectories have been passing from invention to innovation phase.

Nano-sciences studies in “Physics and Earth Sciences” have roughly a relative steady declining trend across geo-economic areas. Studies of nanotechnology in Engineering sciences have also a steady trend across the areas, except for Japan that shows an unstable increasing temporal trend. The results are confirmed by Figure 7, for all geo-economic areas.

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<sup>13</sup> Figure 1A in Appendix A shows the subject areas included in this and other macro subject areas.

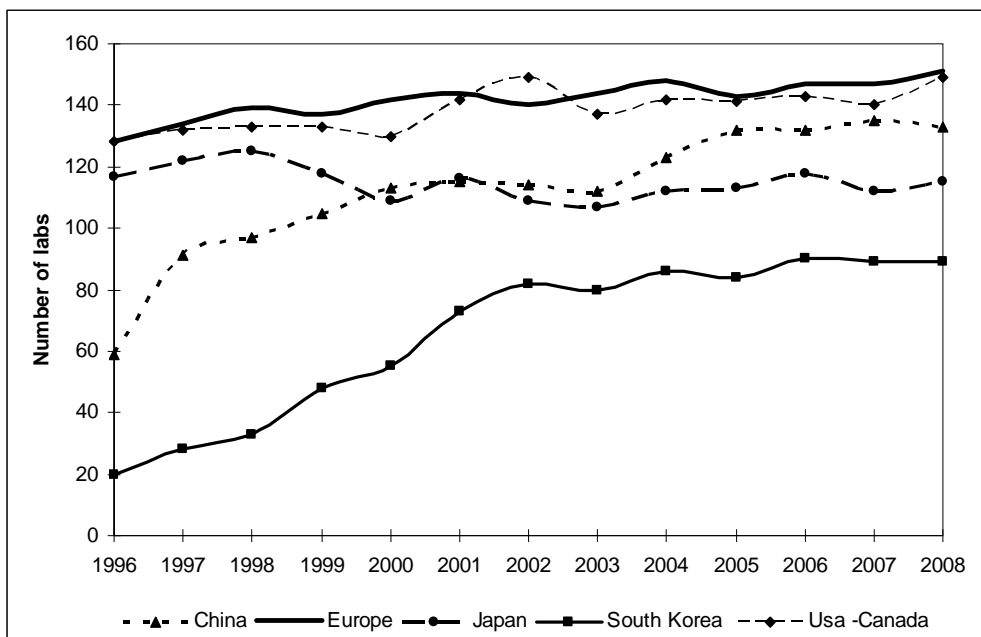


FIGURE 1. RESEARCH CENTRES OPERATING IN NANOTECHNOLOGY ACROSS COUNTRIES, 1996-2008 PERIOD

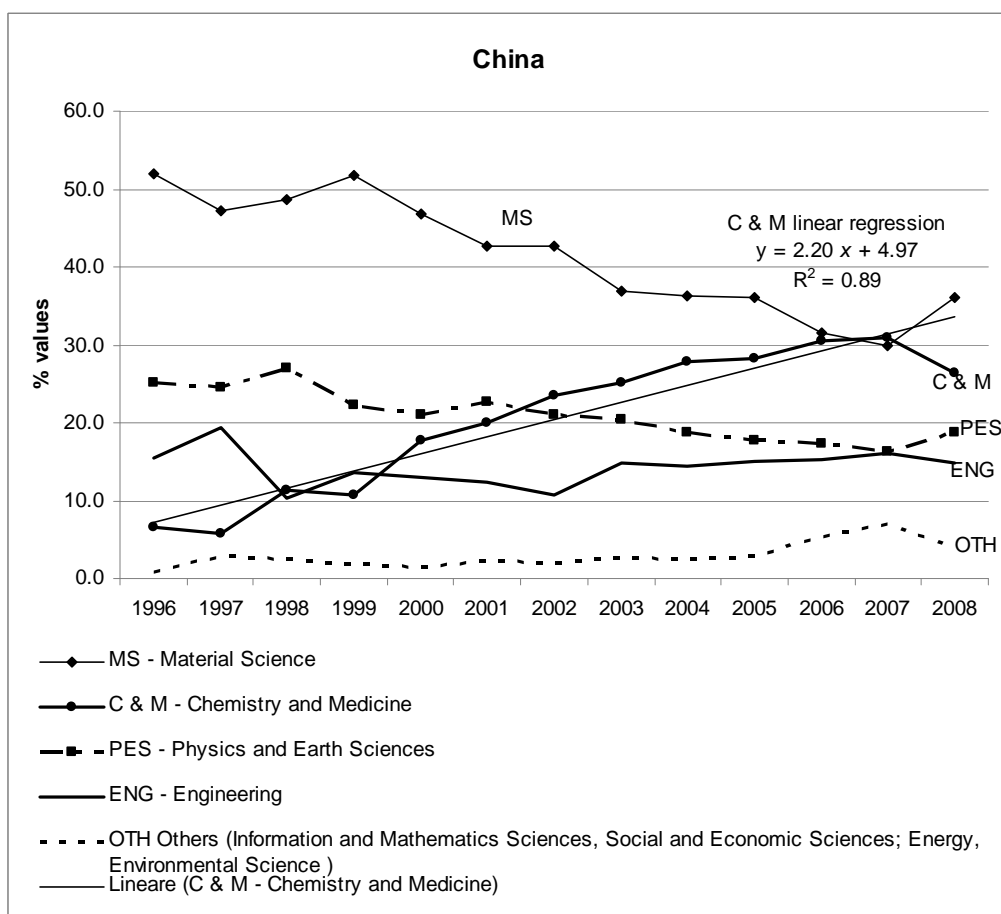


FIGURE 2. RESEARCH TREND MEASURED BY NUMBER OF PAPERS IN NANOTECHNOLOGY STUDIES (% VALUES) CLASSIFIED PER MACRO SUBJECT AREAS – CHINA

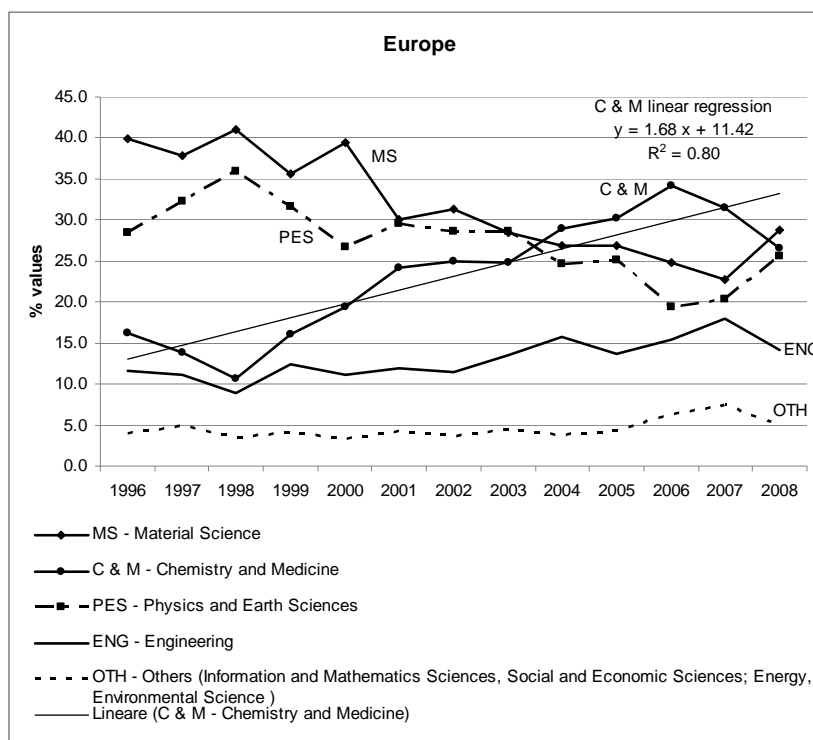


FIGURE 3. RESEARCH TREND MEASURED BY NUMBER OF PAPERS IN NANOTECHNOLOGY STUDIES (% VALUES) CLASSIFIED PER MACRO SUBJECT AREAS - EUROPE

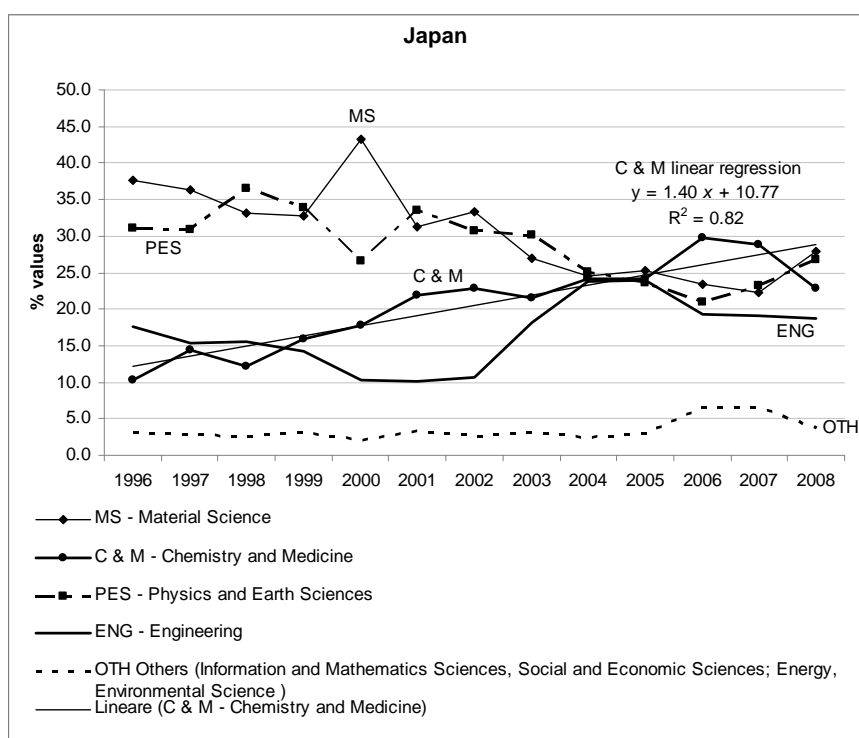


FIGURE 4. RESEARCH TREND MEASURED BY NUMBER OF PAPERS IN NANOTECHNOLOGY STUDIES (% VALUES) CLASSIFIED PER MACRO SUBJECT AREAS - JAPAN

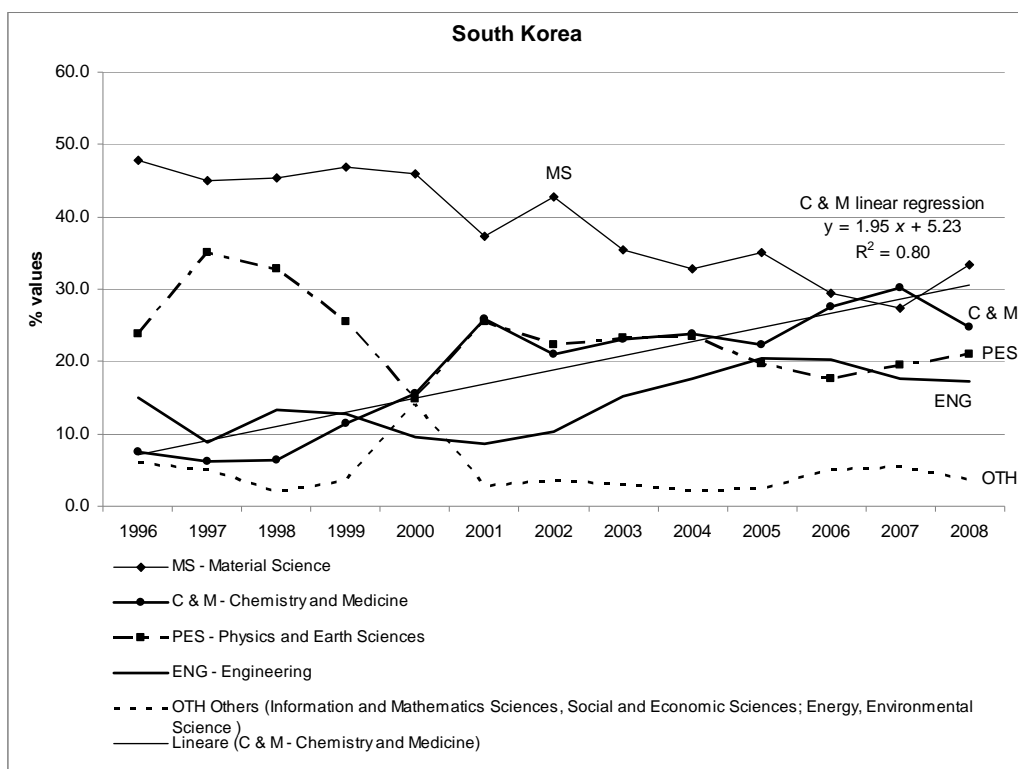


FIGURE 5. RESEARCH TREND MEASURED BY NUMBER OF PAPERS IN NANOTECHNOLOGY STUDIES (% VALUES) CLASSIFIED PER MACRO SUBJECT AREAS - SOUTH KOREA

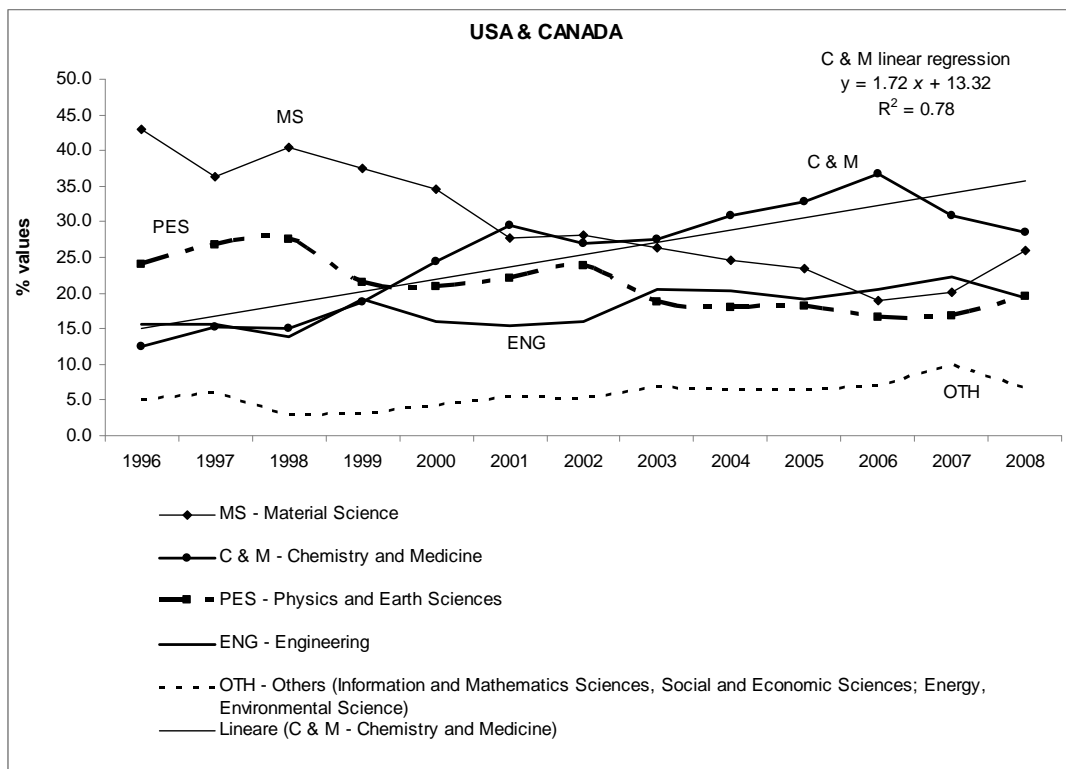


FIGURE 6. RESEARCH TREND MEASURED BY NUMBER OF PAPERS IN NANOTECHNOLOGY STUDIES (% VALUES) CLASSIFIED PER MACRO SUBJECT AREAS - USA & CANADA

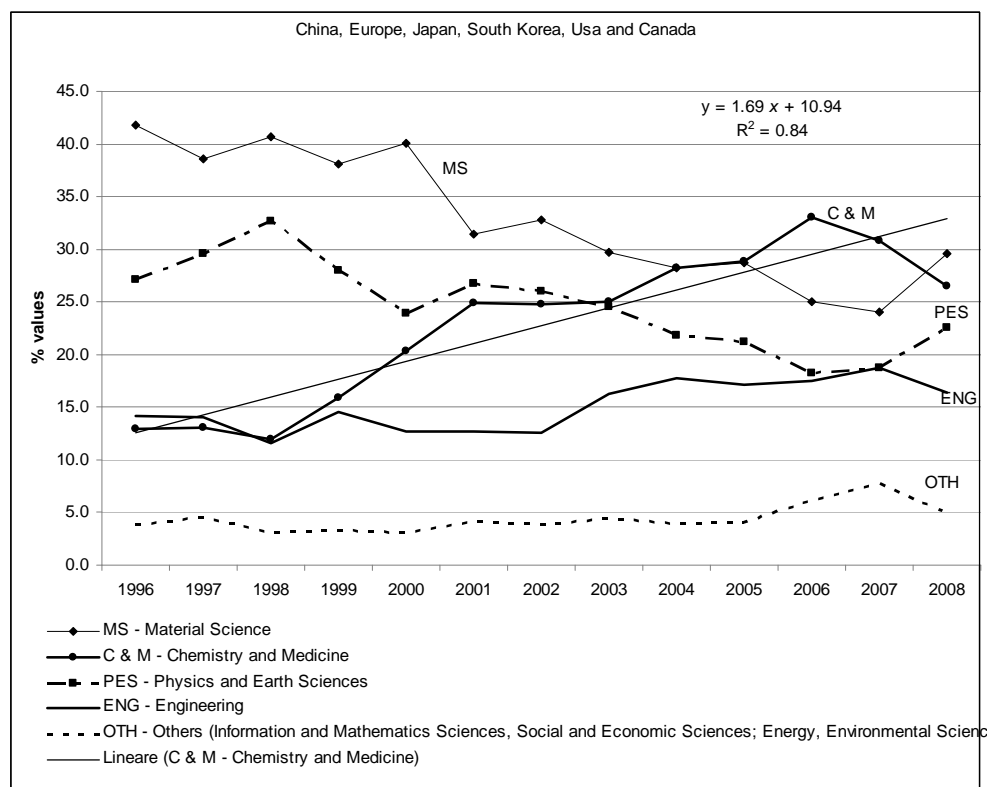


FIGURE 7. RESEARCH TREND MEASURED BY NUMBER OF PAPERS IN NANOTECHNOLOGY STUDIES (% VALUES) CLASSIFIED PER MACRO SUBJECT AREAS – ALL GEO-ECONOMIC AREAS

As the driving nanotechnology studies in “Chemistry and Medicine” have been increasing in the last 15 years with a relative high rate of growth, due to the high number of applications (innovations) in several research fields, the inner dynamics have been divided in two periods (1996-2002 and 2002-2008) in order to capture the temporal paths across countries. Figure 8 shows a relative critical role, over 1996-2002 period, by Europe and USA-Canada, followed by Japan (Third position). If this analysis is repeated over 2002-2008 period (see Figure 9), nanotechnology studies in Chemistry and Medicine carried out in China have been increasing, predominating over the trend of Japan<sup>14</sup> (Fig. 1A and 2A in Appendix show

<sup>14</sup> de Miranda Santo *et al.* (2006) confirm the great contribution of China to scientific research in nanoscience and nanotechnology in the group of competitor countries (p. 1024).

the absolute and percent values of scientific products concerning nanotechnology studies applied in Chemistry and Medicine macro subject area).

Figure 10 shows the Subject Areas of nanotechnology studies included in the macro subject area “Chemistry and Medicine”; these subjects areas confirm the innovation phase of the dynamics of some nanotechnology trajectories.

As far as the nanotechnology studies in “Material sciences” are concerned, the leading countries are mainly Europe and China over 1996-2008 period, although the relative role of China has been increasing over 2002-2008 (Fig. 11 and 12). Other macro areas, *i.e.* “Physics and Earth Sciences” and “Engineering”, show the leadership of Europe and USA-Canada. For the sake of brevity some figures are not reported.

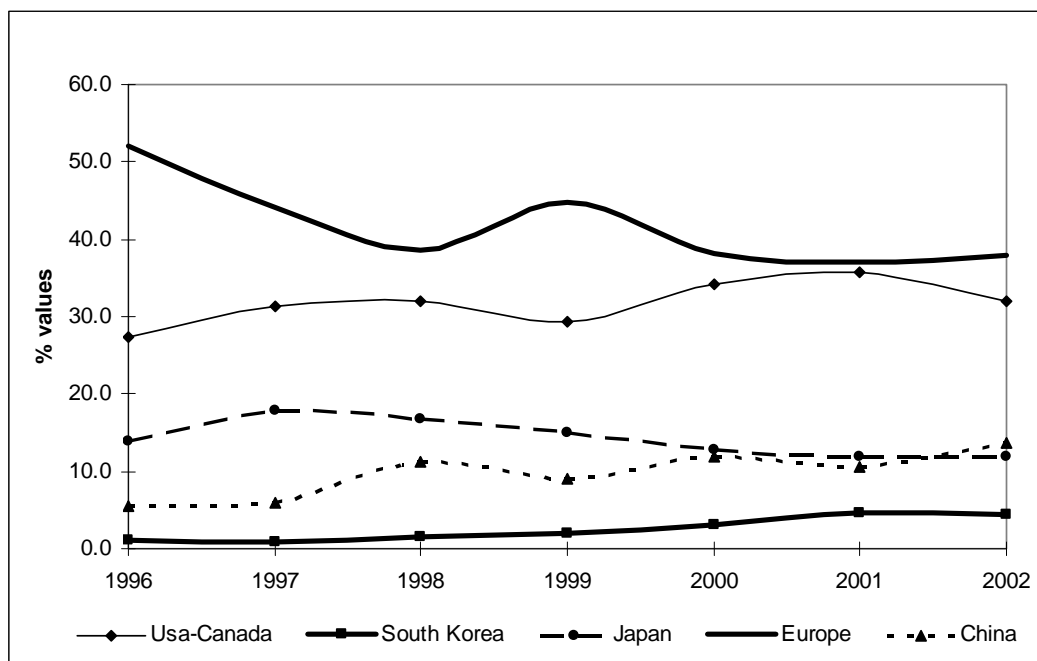


FIGURE 8. RESEARCH TREND PER GEO-ECONOMIC AREAS MEASURED BY NUMBER OF PAPERS IN NANOTECHNOLOGY STUDIES CLASSIFIED IN CHEMISTRY AND MEDICINE OVER 1996-2002 (% VALUES)

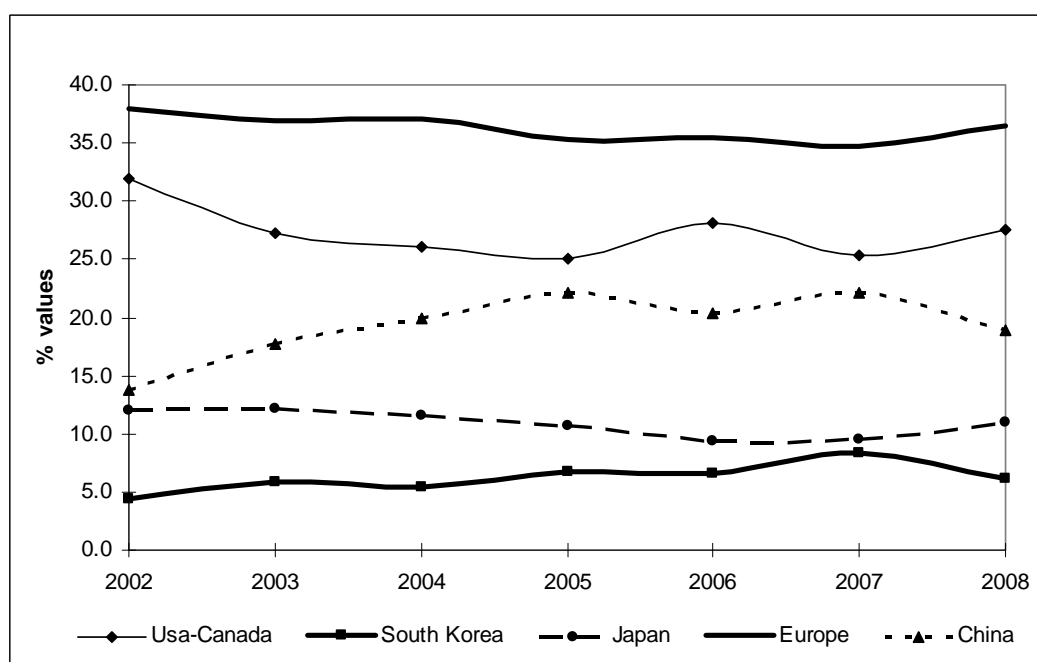


FIGURE 9. RESEARCH TREND PER GEO-ECONOMIC AREAS MEASURED BY NUMBER OF PAPERS IN NANOTECHNOLOGY STUDIES CLASSIFIED IN CHEMISTRY AND MEDICINE OVER 2002-2008 (% VALUES)

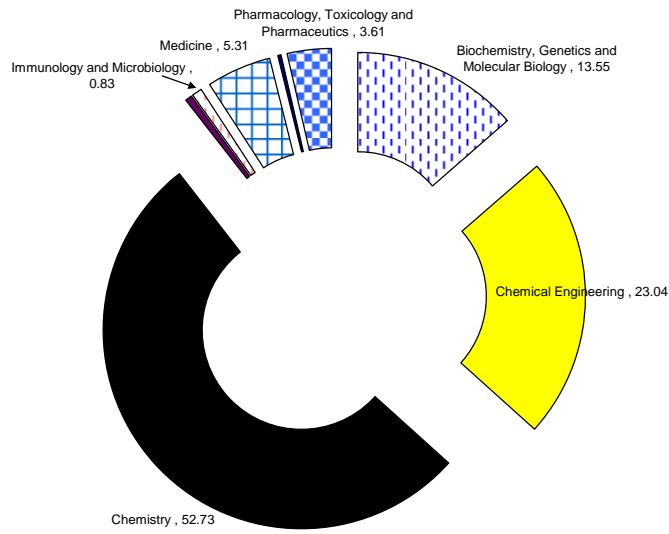


FIGURE 10. PERCENT VALUE OF MAIN RESEARCH FIELDS OF NANOTECHNOLOGY STUDIES APPLIED IN CHEMISTRY AND MEDICINE

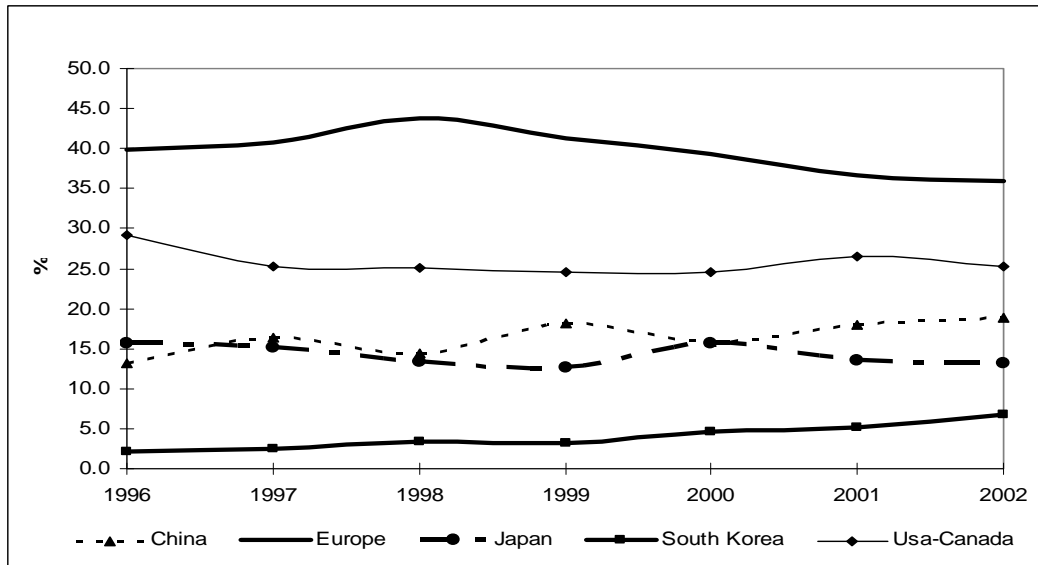


FIGURE 11. RESEARCH TREND PER GEO-ECONOMIC AREAS MEASURED BY NUMBER OF PAPERS IN NANOTECHNOLOGY STUDIES CLASSIFIED IN MATERIAL SCIENCE OVER 1996-2002 (% VALUES)



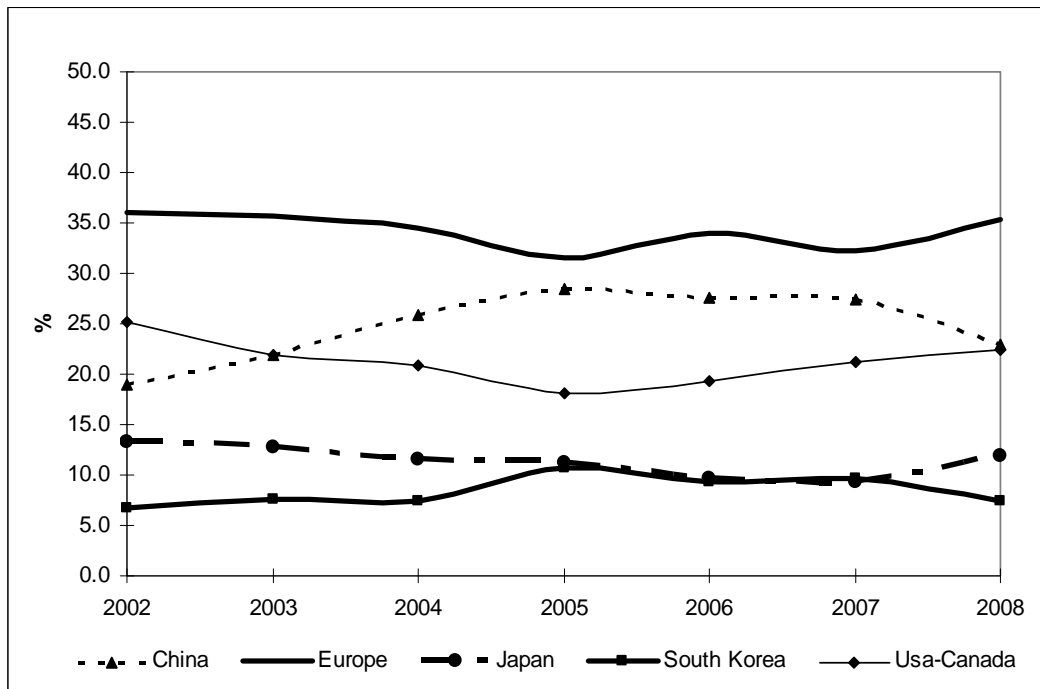


FIGURE 12. RESEARCH TREND PER GEO-ECONOMIC AREAS MEASURED BY NUMBER OF PAPERS IN NANOTECHNOLOGY STUDIES CLASSIFIED IN MATERIAL SCIENCE OVER 2002-2008 (% VALUES)

Another main result is shown in figure 13 about the mutual cooperation across geo-economic areas in nanotechnology studies. Although each geo-economic area has a vast production of scientific outputs within domestic nanotechnology research centres (about 90%), the residual is carried out in collaboration with foreign scholars and research centres. The results are: Europe and

USA-Canada have a high capacity of attraction of foreign scholars in the scientific research on nanotechnology and nanoscience, measured by joint affiliations in papers (see the simple bars above the  $x$ -axis in figure 13), whereas South Korea and China are the two geographic areas having the highest number of scientific collaborations with other scientific players in nanotechnology studies.

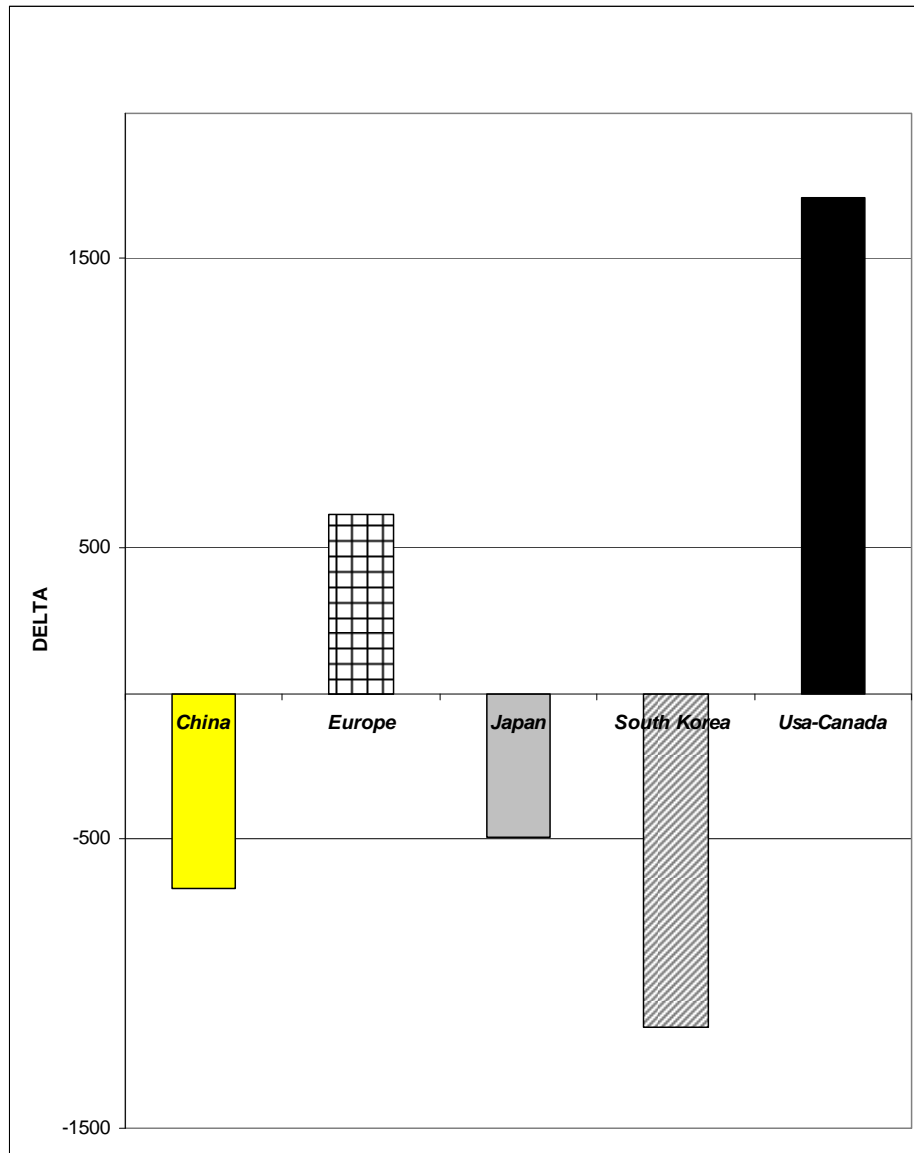


FIGURE 13. RESEARCH ATTRACTION CAPACITY OF FOREIGN SCHOLARS IN NANOTECHNOLOGY RESEARCH PER GEO-ECONOMIC AREAS 1996-2008 PERIOD

*Note:* **DELTA** is the difference between (scientific products in nanotechnology study produced in domestic research centres of the country **A** with foreign institutions) and (scientific products produced by other geo-economic areas in collaboration with research centres of the country **A**); positive delta means high attraction capacity in nanotechnology research by the specific country, *vice versa* negative delta means country with intensive collaborations in nanotechnology research with foreign labs.

## 5. LESSONS LEARNED AND DISCUSSION

The main results of this research are:

- Europe and USA-Canada have the highest number of nanotechnology research centres, although the key role of China has been increasing over time, surpassing Japan.
- Nanotechnology studies in Material Science over 1996-2008 period have a higher scientific production in comparison with other macro subject areas, however there is a relative production increase in the research fields of “Chemistry and Medicine” and a relative production decrease in “Material Sciences”.
- The driving geo-economic areas of nanotechnology studies in “Chemistry and Medicine” are Europe and North America, whereas the relative highest rate of growth is in China and South Korea<sup>15</sup>.
- Main nanotechnology research fields applied in “Chemistry and Medicine” are: Chemistry (~53%), Chemical Engineering (~23%), Biochemistry, Genetics and Molecular Biology (~14%).
- Europe and North America have a high attraction capacity of collaborations in nanotechnology research of scholars from other geo-economic areas, whereas the country with the highest number of collaborations in nanotechnology studies with leading countries is South Korea (over 1996-2008).

*Why Europe and USA-Canada have higher production in nanotechnology studies?*

The determinant can be due to the higher rate of investments in Public R&D in NSTs, that according to Roco (2005) in 2004 were about \$1,100M in the USA (3.7 \$/Capita)<sup>16</sup>,

<sup>15</sup> However, these results based on a linear trends are only an approximation such that should be further examined if they have to be used for forecasting purpose.

<sup>16</sup> “The 2011 Budget provides \$1.8 billion for the National Nanotechnology Initiative (NNI), reflecting steady growth in the NNI investment. The cumulative NNI investment since 2001,

~\$1,050M in EU-25 (2.3 \$/Capita), ~\$950M in Japan (7.4 \$/Capita), ~\$250M in China (0.2 \$/Capita) and ~\$300M in Korea (6.2 \$/Capita). According to Huang *et al.* (2004) the United States have over 60 percent of world nanotechnology patents.

*Why relative NSTs research trend in “Chemistry and Medicine” has been increasing, while “Material Sciences” studies has been decreasing?*

Results on the temporal relative decrease of NSTs studies in “Material science” and increase in “Chemistry and Medicine” can be due to the technology trajectory that have been passing from the invention phase of new nanomaterials to the innovation phase focused on innovative applications in biochemistry, medicine, genetics, etc. In other words, NSTs is a dynamic “new technological system” (Freeman and Soete, 1987, p. 67): some inventions might have become radical and incremental innovations applied in several fields such as chemical engineering and medicine. Islam and Miyazaki (2010) argue that “US has gained much strength in bionanotechnology research relative to other domains, and the other regions (e.g. the EU, Japan, China, South Korea and India) have gained their research strength in nanomaterials, nanoelectronics and nanomanufacturing and tools” (p. 229). In addition, this new “technological system” has different inner nanotechnology trajectories that by cross-fertilization have been generating new “converging technologies” (Bainbridge and Roco, 2006) that are in the first phase of the *S-shaped* curve of growth (Roco, 2007), *i.e.* before the point of inflection: this phase is characterized

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including the 2011 request, now totals almost \$14 billion. Cumulative investments in Environmental, Health and Safety (EHS) research since 2005 now total over \$480 million. Cumulative investments in education and in research on ethical, legal, and other societal dimensions of nanotechnology since 2005 total over \$260 million” (US National Nanotechnology Initiative: <http://www.nano.gov/html/about/funding.html>, accessed 8 June 2010).

by high level of exponential growth that will generate new radical and incremental innovations in not-too-distant future. Roco (2007) also conjectures that the dynamics of nanotechnology outcomes will pass the point of inflection after the year 2020 or thereabouts.

Figure 14 confirms that the development curve of nanotechnology production is not linear, but *S-shaped* over 1996-2008 period, characterized by a disequilibrium pattern of growth. In particular, figure 14 shows the relative higher number of scientific outputs per million people in South Korea and Japan. A critical point is 2002 where the increasing trend of South Korea has been prevailing on

Japan and other geo-economic players. In addition, table 1 shows that R&D investment in nanotechnology as \$/capita is 6.2 in South Korea, lower than Japan (7.4). However, NSTs outcome in South Korea is of 27.92 scientific products per million people, a higher value than Japan (22.30). This gap is higher if the scientific performances of 2008 are considered: 41.98 scientific products (in nanotechnology) per million people in South Korea vs. 19.93 in Japan. Therefore these results show that the specificity of national sub-set of nanotechnology in South Korea has more efficiency in comparison with Japan and other geo-economic areas.

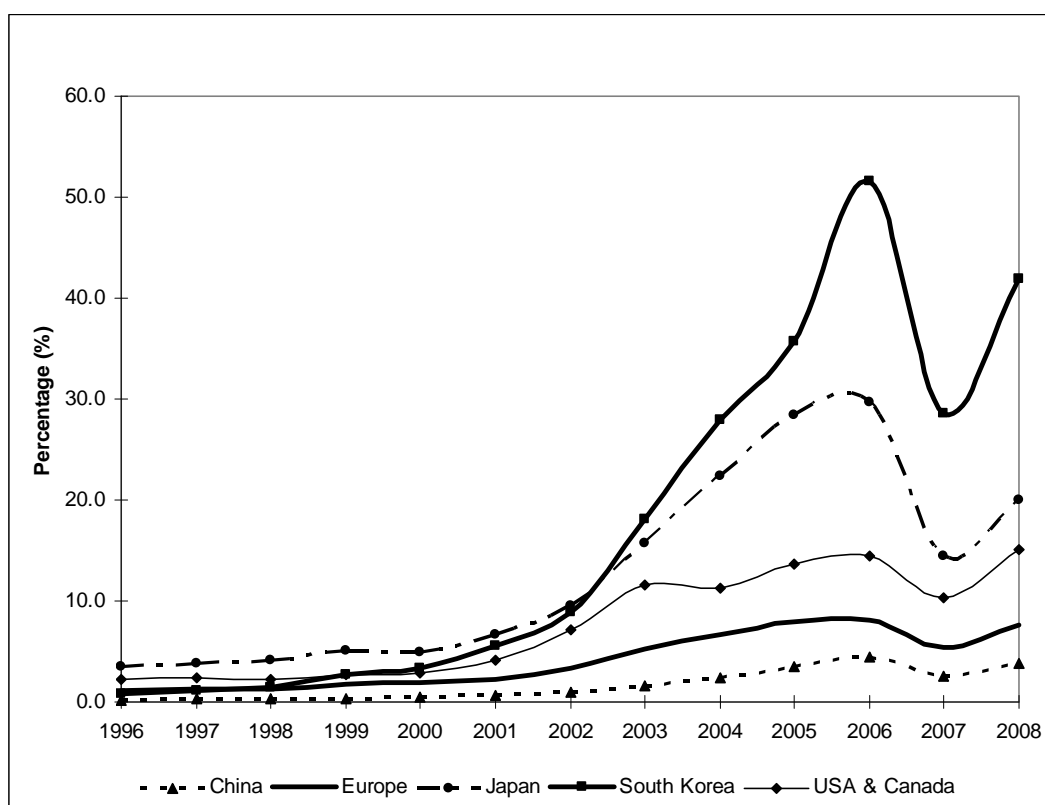


FIGURE 14. SCIENTIFIC PRODUCTS IN NSTs PER MILLION PEOPLE ACROSS GEO-ECONOMIC AREAS OVER 1996-2008

TABLE 1. RESEARCH INVESTMENTS AND SCIENTIFIC PERFORMANCE IN NANOTECHNOLOGY STUDIES ACROSS COUNTRIES

Countries	Specific. Nanotech R & D 2004 (\$ / Capita)*	Nanotechnology scientific products per million people 2004	Nanotechnology scientific products per million people 2008	$\Delta$ %
USA	3.7	11.28	15.07	33.60
Europe	2.3	6.62	7.65	15.56
Japan	7.4	22.30	19.93	-10.63
China	0.2	2.40	3.80	58.33
South-Korea	6.2	27.92	41.98	50.36

\* Source: Roco (2007), pp. 3.1-3.26

This research shows main worldwide research trends of NSTs studies, though the results could have some limits. The main one is that Scopus retrieves the first 160 results for each item (Source, Affiliation, Keyword, etc.) set by Scopus to Data mining; in addition, Scopus is a relatively new instrument for scientific literature classification and not all nanotechnology research might be included (though this limit is common with other web-based datasets).

Although “nanotechnology is still in an early phase of development” (Renn and Roco, 2006, p. 153), these results show the current growing applications of nanotechnology in some key sectors, such as Chemistry and Medicine<sup>17</sup>, which may imply some ethical and social issues that Governments might need to face in the next future in order to support a sustainable development of pattern of technological innovation and economic growth as well.

Renn and Roco (2006, p. 154) argue:

As with other new technology, nanotechnology evokes enthusiasm and high expectations: for new progress in science and technology, new productive applications and economic potential on one hand; and for concerns about risks and unforeseen side effects on the other.

<sup>17</sup> According to de Miranda Santo *et al.* (2006) “many areas will suffer impacts caused by Nanoscience and Nanotechnology [...] as health, chemistry and petrochemicals, computing, Energy, agribusiness, metallurgy, textiles, environmental protection, among other” (p. 1020).

Renn and Roco (2006) also claim the general risks associated with nanotechnology applications, showing that the nanotechnology innovation proceeds ahead of the policy and regulatory contexts: “Governance gap is [...] especially significant for the several ‘active’ nanoscale structures and nanosystems that [...] have the potential to affect not only the human health and the environment but also aspects of social lifestyle human identity and cultural values” (p. 153, original emphasis). Robinson (2009) describes the notion of “*Responsible Research and Innovation*” of nanotechnology as an opportunity to develop support tools for exploring potential co-evolutions of nanotechnology and governance arrangements. This involved the inclusion of pre-engagement analysis of potential co-evolutions in the form of scenarios into interactive workshop activities with the aim of enabling multi-stakeholder anticipation of the complexities of co-evolution” (p. 1222, original emphasis).

No doubt that information analysis and foresight studies for research trends of NSTs are a hard work since this technological system is characterized by “interdisciplinarity” and “pervasiveness” (Salerno *et al.*, 2008, p. 1206, 1208, and 1220, *passim*) in the current disequilibrium phase of growth. In presence of these scientific and analytical issues, further research about these research trends is needed

to strengthen this important topic in economics of innovation in order to design provident innovation policy and governance practices aimed at driving sustainable paths of growth for modern economies that are more and more based on these “new converging innovations” (cf. Bainbridge and Roco, 2006) within the technological system of nanotechnology.

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## APPENDIX A

TABLE 1A: AGGREGATION OF SUBJECT AREAS IN MACRO SUBJECT AREAS IN NSTs STUDIES

<i>Macro Subject Area</i>	<i>Subjects Area (S.A.)</i>	<i>Total papers in S.A.</i>	<i>Total papers in Macro S.A.</i>	<i>%</i>
Material Science	Materials Science	117,808	<b>117,808</b>	29.46
Chemistry and Medicine	Biochemistry, Genetics and Molecular Biology	14,471		3.62
	Chemical Engineering	24,617		6.16
	Chemistry	56,329		14.09
	Dentistry	212		0.05
	Health Professions	376		0.09
	Immunology and Microbiology	889		0.22
	Medicine	5,677		1.42
	Veterinary	42		0.01
	Neuroscience	336		0.08
	Nursing	30		0.01
	Pharmacology, Toxicology and Pharmaceutics	3,855		0.96
			<b>106,834</b>	
Physics and Earth Sciences	Earth and Planetary Sciences	1,555		0.39
	Physics and Astronomy	88,418		22.11
			<b>89,973</b>	
Engineering	Engineering	65,421		16.36
			<b>65,421</b>	
Information and Mathematics Sciences	Mathematics	2,061		0.52
	Computer Science	5,794		1.45
	Decision Sciences	86		0.02
			<b>7,941</b>	
Social and Economic Sciences	Arts and Humanities	266		0.07
	Business, Management and Accounting	562		0.14
	Economics, Econometrics and Finance	82		0.02
	Multidisciplinary	2,412		0.60
	Psychology	75		0.02
	Social Sciences	680		0.17
			<b>4,077</b>	
Energy	Energy	3,921		0.98
			<b>3,921</b>	
Environmental Science	Agricultural and Biological Sciences	770		0.19
	Environmental Science	3,086		0.77
			<b>3,856</b>	
<b>TOTAL</b>		<b>399,831</b>	<b>399,831</b>	<b>100.00</b>

*Note:* Scopus classifies journals in major subject areas, e.g. “Energy”. Journals can be allocated to multiple subject areas as appropriate to their scope. The subject areas contain scientific products concerning nanotechnology studies.



TABLE 2A: NUMBERS OF SCIENTIFIC PRODUCTS IN NANOTECHNOLOGY STUDIES PER SUBJECT AND MACRO SUBJECT AREAS OVER 1996-2008 ACROSS ALL GEO-ECONOMIC AREAS

<i>Number</i>	<i>Macro Subject Area (8)</i>	<i>Papers</i>	<i>Macro Subject Area (5)</i>	<i>Papers</i>
1	Material Science	117,808	Material Science	117,808
2	Chemistry and Medicine	106,834	Chemistry and Medicine	106,834
3	Physics and Earth Sciences	89,973	Physics and Earth Sciences	89,973
4	Engineering	65,421	Engineering	65,421
5	Information and Mathematics Sciences	7,941		
6	Social and Economic Sciences	4,077		
7	Energy	3,921		
8	Environmental Science	3,856	Others	19,795

TABLE 3A: CUMULATIVE NSTs RESEARCH CENTRES AND THEIR SCIENTIFIC PRODUCTS IN NANOTECHNOLOGY STUDIES OVER 1996-2008 ACROSS GEO-ECONOMIC AREAS

<i>Year</i>	<i>China</i>		<i>Europe</i>		<i>Japan</i>		<i>South Korea</i>		<i>USA-Canada</i>	
	<i>Labs</i>	<i>Scientific products*</i>	<i>Labs</i>	<i>Scientific products*</i>	<i>Labs</i>	<i>Scientific products*</i>	<i>Labs</i>	<i>Scientific products*</i>	<i>Labs</i>	<i>Scientific products*</i>
1996	59	210	128	675	117	430	20	37	128	673
1997	91	312	134	856	122	483	28	51	132	700
1998	97	414	139	874	125	519	33	68	133	670
1999	105	467	137	1,135	118	645	48	124	133	841
2000	113	612	142	1,234	109	621	55	159	130	878
2001	115	780	144	1,414	116	848	73	260	142	1,294
2002	114	1,185	140	2,122	109	1,214	82	425	149	2,264
2003	112	2,001	144	3,404	107	1,993	80	864	137	3,696
2004	123	3,070	148	4,313	112	2,836	86	1,330	142	3,607
2005	132	4,476	143	5,167	113	3,607	84	1,705	141	4,375
2006	132	5,760	147	5,280	118	3,780	90	2,460	143	4,601
2007	135	3,324	147	3,556	112	1,834	89	1,363	140	3,301
2008	133	4,864	151	4,980	115	2,534	89	2,000	149	4,819
<b>Total</b>										
<b>1996-2008</b>	<b>1,461</b>	<b>27,475</b>	<b>1,844</b>	<b>35,010</b>	<b>1,493</b>	<b>21,344</b>	<b>857</b>	<b>10,846</b>	<b>1,799</b>	<b>31,719</b>

\* Scientific products are papers, proceedings, etc.

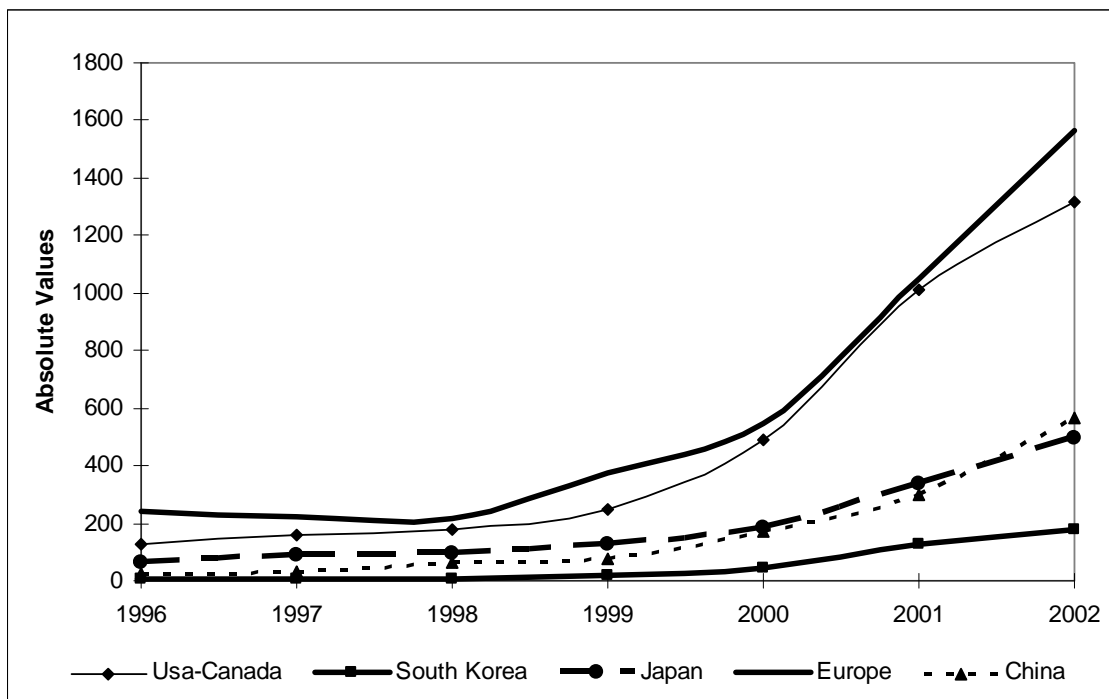


FIGURE 1A. RESEARCH TREND PER GEO-ECONOMIC AREAS MEASURED BY NUMBER OF SCIENTIFIC PRODUCTS CONCERNING NSTs STUDIES CLASSIFIED IN CHEMISTRY AND MEDICINE OVER 1996-2002 (ABSOLUTE VALUES)

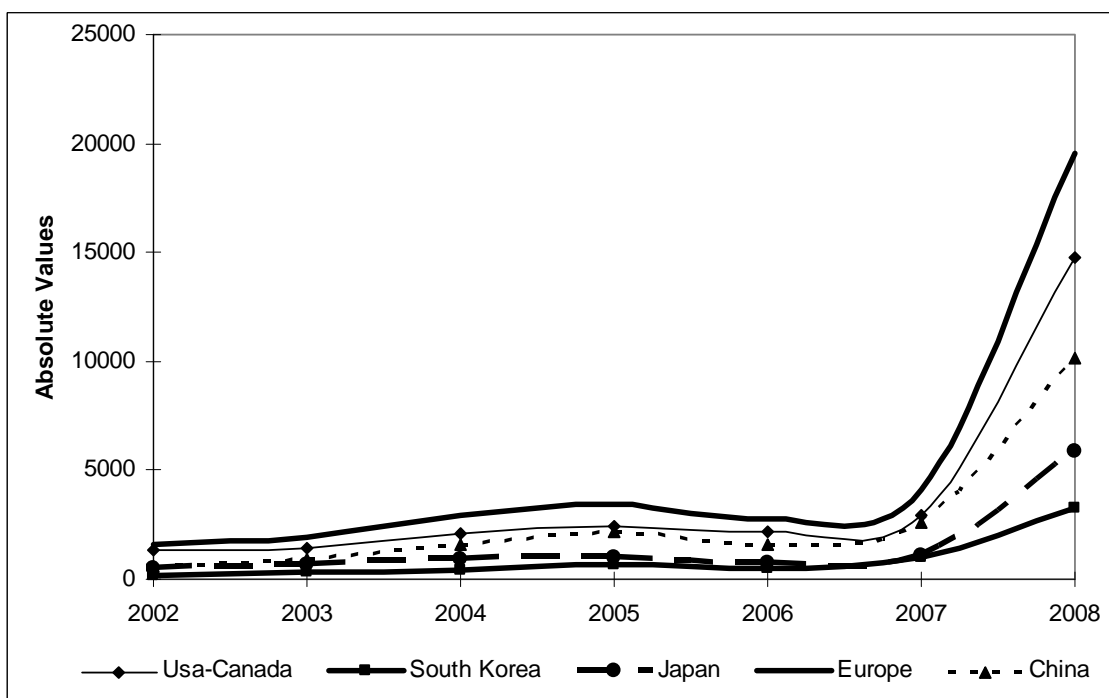


FIGURE 2A. RESEARCH TREND PER GEO-ECONOMIC AREAS MEASURED BY NUMBER OF SCIENTIFIC PRODUCTS CONCERNING NSTs STUDIES CLASSIFIED IN CHEMISTRY AND MEDICINE OVER 2002-2008 (ABSOLUTE VALUES)

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