

The management of nanotechnology: Analysis of technology linkages and the regional nanotechnology competencies

Abstract

This study maps linkage of nanotechnologies and their clusters; identifies emerging and mature technologies and links to their application fields; and examines the profiles of regional nanotechnology competencies. A model is proposed to assist with the analyses. The patent data were retrieved from the Thomson Innovation database, which were subsequently analysed with the Thomson Data Analyser (TDA). The results show technological linkages using the proposed linkage model, for example, the linkage between the cluster of nanotubes-nanowires-polymers and the cluster of nanowires-semiconductors-optical identifies a nanoelectronics domain. In the Techno-Economic Network (TEN) framework, the result shows that the US maintains its position in the Science and Technology poles, revealing its strong competitiveness, while the nanotechnological competencies in Japan have lost strength significantly in recent years. Asian giants such as South Korea and China appear to be the most likely contenders for catching up with the US. The theoretical contribution of this study is the theoretical framework that has been adapted and tested in this research. Practical contributions consist of descriptive and analytical findings based on actors' performances and the regions' competencies. The research offers a useful insight for academic and research practitioners on how an emerging field such as nanotechnology can be analysed, and a way forward for materialising science and technology policies in this field.

Keywords: nanotechnology; technology linkages; competencies; patents; Themescape mapping; revealed technological advantages

1 Introduction

Nanotechnology is still a growing area and is considered to be an emerging technology (Bozeman et al., 2007; Linton and Walsh, 2008; Islam and Miyazaki, 2009). The progress of nanotechnological developments and innovations, and their diffusion into various industries, is changing fast as nanotechnology is a highly vibrant emerging field. Over the past few years, several attempts have been made to study nanoscience and technology management (for example, three highly ranked journals called '*Research Policy*', '*Technological Forecasting & Social Change*' and '*Technovation*' have published special issues on nanotechnology). If one looks at similar methodological approaches in similar fields by other authors, one finds various bibliometric studies (Braun et al., 1997) on patent and publication documents with the aim of understanding innovation systems in nanotechnology from a sectoral basis to a national or global one (Miyazaki and Islam, 2007; Porter and Youtie, 2009; Shapira et al., 2011; Huang et al., 2003; Goetze, 2010; Cheng, 2012; Lee et al., 2009; Islam and Ozcan, 2013; Abraham and Moitra, 2001; Encaoua et al., 2006; Faber and Heslen, 2004; Wu and Lee, 2007; Ozcan and Islam, 2014), while others focus on technological advances and economic progress

(Greif, 1992; Ma et al., 2009; Hidalgo et al., 2010; Bachmann, 1998; Trappey et al., 2011; Tseng, 2011). Patent data were chosen as the data sources for this study because patent data are considered to be a valuable source of information in the innovation management field, for example, for identifying promising technologies and assessing technological advances and new trends, recognising types of linkages between actors and for forecasting technological change (Archibugi and Planta, 1996). The main emphasis of this study is to examine technology linkages and regional technology competencies using the systems of innovation approach, which comprises the linkages and flow of information among actors, such as inventors and organisations, in terms of innovation processes (Lundvall, 1992; Liu and White, 2001; Doloreux, 2002; Yim and Kang, 2008; Guan and Chen, 2012), and patents are one of the sources to enable the identification of where, when and how these relationships occur.

A review of the previous literature indicated that there were certain limitations to the existing research. These limitations could be divided into those concerned with the methodology applied and the type of research. In terms of methodology, previous studies used a different data collection method. For example, Huang et al. (2011) categorised lexical and patent classification queries by analysing related methodological studies. Porter et al. (2008), Mogoutov and Kahane (2007) and other similar studies have used lexical queries to gather all patents with 'nano' terms, which resulted in a total of around 140,000 patents, though many were unrelated. However, Porter's (2008) lexical search query appears to be one of the most reliable for publication data gathering, since there is no possibility of using a combination of patent classification codes with lexical queries in this category. Given the limitations and drawbacks of the existing approaches (Huang et al., 2003; Scheu et al., 2006; Porter et al., 2008), this research sets out to develop an improved method which uses a combination of both patent classification codes and lexical queries. This approach helps accurate nanotechnology patent retrieval. In terms of relevant research, existing studies (Ma and Lee, 2008; Petruzzelli, 2011; Genet et al., 2012; Guan and Zhao, 2013) lack the degree of investigation of nanotechnological dynamics as opposed to the present study, which focuses on technology linkages and the competitive strengths of specialisation in the nanotechnology field.

Through the use of extensive patent analysis, this paper maps linkage of technologies and their clusters, classifies mature and emerging technologies and their application domains, and examines the profiles of regional nanotechnology competencies. Focusing on linkage mechanisms and the strength of the degree of specialisation of countries and regions introduces a different level of analysis, and this could present different outcomes for technology management specialists and patent analysts. We think this should make a worthy contribution to the literature, methodology and practice concerning the acquisition of nano-knowledge and its exploitation in the field of management of innovation, science and technology.

2 Literature and analytical framework

This study draws upon two streams of literature to set the foundation for our analysis of technology linkages and regional competencies in the nanotechnology field, namely, systems of innovation and techno-economic network theories. We look at the systems of innovation theory (Freeman, 1991; Lundvall, 1992; Nelson, 1993; Edquist, 1997) in terms of the interactions of various actors in technology development and diffusion within the system. This approach stresses the importance of knowledge flows in innovation processes and their application at different levels: national, regional, sectoral and technological (Lundvall, 1992; Nelson, 1993; Freeman, 1995; Cooke and Morgan, 1994, 1998; Malerba, 2004; Carlson and Stankiewicz, 1991). Understanding innovation systems can lead policy makers to suggest strategies that best enhance innovative performance and overall competitiveness, and to identify bottlenecks within a system that can hinder technology development and diffusion.

A versatile and useful method for characterising innovation systems based on the actors and their activities is provided by the Techno-Economic Network (TEN) (Figure 1) – network of interactions among actors – which elucidates the emergence and diffusion of technological innovations and which proposes three major poles, namely, the Science, Technology and Market poles (Callon and Bell, 1991). A TEN framework can be adapted for a system of innovation study by using patent information in order to examine the linkages of actors in various poles. With analyses of the linkages, it should be possible to see how current technology sources are generated and how these actors are linked to each other within an innovation system.

[Insert Figure 1 here]

Reviewing existing nanotechnology-related studies (OECD, 2009; Islam and Ozcan, 2013; Zheng et al., 2014) proved that the top nations (e.g. USA, Japan, China, South Korea, Germany) hold over 90% of patent share and lead the technological competencies in nanotechnology fields. It is essential to examine the leading nations' involvement in technology capabilities, as nanotechnology is a field where the technological strengths and foci of each country may differ. The countries included in this analysis are: the United States, Japan, China, South Korea, Germany, France, United Kingdom and Russia. These countries were selected on the basis of their predominant roles in the field of nanotechnology. It may be beneficial to identify the Revealed Technological Advantage (RTA) of leading nations, as they influence nanotechnology-driven industry. This paper aims to answer the following: how nanotechnology's technological linkages are shaped due to its multidisciplinary nature; where the linkages between technological domains occur and their causes; and how the trend of technology competencies is changing with respect to the leading nations' involvement in nanotechnology.

Given nanotechnology's multidisciplinary nature, it is to be expected that technology domains will be linked to each other at various levels. To assist with the process of the linkages of technologies and clusters, a new technology linkage model is being proposed as an analytical framework (Figure 2) to illustrate a possible scenario of technology linkages in different scientific disciplines and technology domains. The proposed model assumes that the nanotechnology field is diffused among different scientific areas and technology domains. As such, it is to be expected that there are linkages within the same discipline or across disciplines with some particular patents. Moreover, one can assume there will be diffusion in terms of patent usage in some applications as they may require multiple patents from different patent owners. Figure 2 makes use of various components and sub-components to illustrate a possible scenario of technological development in multidisciplinary fields such as nanotechnology and biotechnology. Accordingly, it can be assumed that fundamental research in any scientific field leads to an opportunity of having applied research that results in patents and commercial applications. This new technological progress forms a technological domain (e.g. materials, electronics) that will be linked to a certain field such as Chemistry. In the nanotechnology area, these technological advances are not unidirectional but a combination of research efforts in different scientific fields and technological domains. Looking at patent clusters and how they are linked, it is possible to identify which fields and technological domains are linked to each other. Analysis of prevalent patent clusters and their linkages will reveal key technologies and their linkage mechanisms in the nanotechnology field.

[Insert Figure 2 here]

The nanotechnology field is one of the key areas for collaboration-related studies due to its intense level of research participation across disciplines and sectors and its involvement of various actors. The complex task of integrating different disciplines and fields involves creating new business structures, new management models and new systems. Therefore, it requires new systems to enable these changes and hybrid individuals that can fulfil the requirements of different fields. Considering the research nature and characteristics of the nanotechnology field, it appears to be essential to conduct in-depth research in this area to throw light on the above issues.

3 Research design

Patent analyses have been used extensively in research for a number of purposes including identification of new technology opportunities (Lee et al., 2009), technology networks and diffusion (Goetze, 2010; Cheng, 2012) and forecasting technologies (Daim et al., 2006). Compared with the majority of quantitative methods in business studies, patent data mining studies are less frequent and it is still a developing field. Moreover, many nanotechnology-related patent studies only started emerging from the late 1990s and the beginning of this millennium, so this is an important area to

work on. This research applies a tech-mining method (Porter and Cunningham, 2005) which has had a significant impact on the analysis of technology dynamics. The outline of the research design is shown in Table 1. The data for this study was retrieved from the Thomson Innovation database and analysed using the tech-mining software Thomson Data Analyser (TDA), which automates mining and clustering of terms occurring in patent abstracts and descriptors according to authors, affiliations or keywords that it recommends. The TDA allows the analysis of patent data and their visualisation in many ways, such as cleaning the data of duplicates or unnecessary items, mapping, clustering, co-occurrence, factor analysis and citation networks. After collecting the patent dataset, there are still certain steps which need to be taken to optimise the data, for example, eliminating duplicates by obtaining patent data with the DWPI (Derwent Patent Index) and preparing categories and groups for analysis.

[Insert Table 1 here]

After optimisation is completed, various analyses can be undertaken, such as trend, landscape, network, patent portfolio, citation and topological analyses. For this, the TDA is used as it performs multidimensional statistical analysis to identify clusters and relationships among nodes. Each cluster is represented by nodes, the size of a node representing the number of patent documents that belongs to it, while its centrality represents how often that particular node occurs with other nodes. The closeness of nodes and their thicknesses are calculated on the basis of the significance and interrelationship level between each node, which in turn is calculated on the basis of how many of those documents belong to the node and how many of those documents are shared.

In addition to the TDA, another offering of Thomson Innovation called the Themescape tool can be used. Themescape extracts text terms from a set of patent records and generates a topological map showing the frequency of a term's occurrence as apparent peaks on a geographical island. Themescape was used to map key technologies and allowed the categorisation of documents containing similar content, as they were placed near each other on the map. The density of documents can be indicated with tall or small peaks and the distance between peaks sheds light on the relationship between content, as peaks that are located closer to each other have more closely related content than peaks that are located farther away. Contour lines indicate relative document density and by using the tool it is possible to zoom in on a specific area whereby new contours, labels and documents can be revealed.

This research also maps the profile of the nanotechnological competencies for nations. The patent data were converted to calculate the relative technological advantages of regions in nanotechnology. The Revealed Technological Advantage (RTA) index (Cantwell, 1993; Patel and Pavitt, 1997; OECD, 2011) provides an indication of the relative specialisation of a given country in selected technological domains. A value above 1 indicates relative strength and a value less than 1 indicates relative

weakness. The regions of high share and high RTA can be interpreted as being countries with a relatively strong share in the Technology pole (i.e. relative importance to competencies in nanotechnology) and having distinctive advantages nationally. The region of low share and low RTA reveals countries allocating relatively fewer resources to technology or science and having less distinctive advantages nationally. It is to be noted that the value of the benchmark share in the X-axis is difficult to identify and varies depending on various dimensions such as the countries or region considered, innovation process analysed, national requirements etc. In this case, a break-even share has been chosen in order to accommodate all countries in such a way that a proper comparison of their technological or innovation performance can be made. Therefore, in this analysis, what matters is the direction of movement and comparative positions rather than absolute positions.

One of the biggest challenges in a patent analysis is to gather required patent data by selecting the appropriate search terms so that the data set includes the relevant patents and excludes unnecessary patents, thus increasing the validity of the research. This study offers a more effective method with an improved patent search query which uses a combination of both patent classifications and lexical queries to exclude unrelated patents. Considering the limitations and drawbacks of existing patent data collection approaches the following search approach and terms were used:

(AIOE=(B82*) OR FIC=(B82*) OR UCC=(977*)) AND ALLD=(nano* OR quantum* OR Qdot OR Qubit OR atom* OR probe OR epitax* OR fullerene* OR thin ADJ wire* OR thin ADJ film* OR buckyball* OR scanning ADJ microscope* OR tunnelling ADJ microscope* OR scanning ADJ electron* OR bionano* OR bio-nano* OR gCNT* OR Peapod* OR CSCNT* OR CNT* OR g-CNT* OR colloidal ADJ crystal*)

The patent data collection and filtration process is illustrated in Figure 3, which shows how the required patents were collected. 49,544 individual nanotechnology patents were obtained after optimisation for the period of 1970–2012. The optimised data were imported into the TDA to validate the results further. Duplicate results were eliminated and variations of company, inventor, institutes and university names were unified where they appeared as separate patent assignees. After the dataset was cleaned and prepared, various functions offered by the TDA were utilised to generate the required analysis.

[Insert Figure 3 here]

4 Results

4.1 *Nanotechnology patent contribution by Corporate-Academic-Inventors*

Previous studies have failed to investigate nanotechnological developments with respect to their provenance, be that academic, industrial or sole inventor. The benefit of this section is to show where

academia's, industry's or inventors' foci are in terms of technological domains. Table 2 illustrates the extent to which academic, industrial and sole-inventor involvement differs by country. In the US, Japan, Germany and the UK, corporate actors have a greater involvement than academic organisations. This is mainly due to the presence in these regions of large corporate players with an interest in patenting their technologies. Another reason why patenting activity is predominantly business driven in these countries is that they are host to the world's largest electronics corporations (such as IBM in the US and NEC in Japan), which perceive themselves as having a significant vested interest in nanotechnological applications.

In China, Russia and Taiwan, academic institutions are more heavily involved than their corporate counterparts, an unexpected outcome given the nature of their patenting activities. These results have been combined with interview analyses in order to understand why these three countries have higher levels of academic involvement. In China's case, interviews with key experts in the Chinese Academy of Sciences and Tsinghua University were conducted and it was found that this is mainly due to state policy on funding: academia is allotted the largest funding share and there are relatively few sources of funding made available for academic-industrial collaborations. In addition, China's patenting system is politically driven and gives considerable support and motivation to academia to file patents. Patent filing is closely linked to promotion, the award of bonuses and further research grants, and is prioritised over publications.

[Insert Table 2 here]

In this section, patent classifications are used to examine academic, corporate and inventor involvement and to discover in which technologies they are highly concentrated. Table 3 shows that while the significant patent share is held by industrial players, as is to be expected, academic involvement is still noteworthy. In the fields of E (General Chemicals), B (Pharmaceuticals), S (Instrumentation, Measuring and Testing) and D (Food, Detergents, Water Treatment and Biotechnology), academic involvement is almost at the contender level or at the same level as that of corporate players.

[Insert Table 3 here]

4.2 Key technologies and their links to application fields

This research identifies mature and emerging technologies in the nanotechnology field and their applicability to relevant market domains. Table 4 shows some of the mature technologies such as V08-A04A (semiconductor laser), U12-E01B2 (semiconductor body with quantum wire, wells, superlattices) and U11-C01J6 (semiconductor materials and processing, strained layers and their

manufacture). Accordingly, it is reasonable to assume that nanotechnology inventions with semiconductor materials and applications are relatively mature compared to other nanotechnologies. Looking at the emerging technologies, A12-W14 (polymer applications with nanotechnology) appears to be the most rapidly developing technology area in this field, as in 2004 there were only 72 patent records while this increased to 1,283 records in the peak year of 2008 (see Figure 4). Moreover, almost 35% of the patents appear to have been granted in the last 3 years. Another emerging technology is U11-A14 (nano-structural materials) for which 23% of patents have been granted in the last 3 years. The peak point for U11-A14 was in 2006 with 393 patent records, while in 2003 there were only 47 patent records. Between 2006 and 2009, there were over 300 patents granted for nano-structural materials each year.

Another technology within the nanotechnology field that has shown promising growth in recent years is E05-U03 (carbon nanotubes). Carbon nanotubes (CNTs) had only 4 patents in 2000, but this gradually increased to 417 patents in its peak year of 2004. Between 2004 and 2009, the number of patents in the CNT field was always higher than 350 patents per year. The rapid increase in CNT patent documents is due to the recognised importance of this nanostructure in a very broad field.

[Insert Figure 4 here]

Professor Fan Shoushan¹ was interviewed to help elucidate the findings of this research even further. A successful example can be given to show how an interlinked activity is turned into a commercial product through the efforts of both parties (a linkage between Tsinghua University and Foxconn). Since nanotubes were first invented, Tsinghua University has gained the capability of controlling the growth of CNTs and of transferring CNTs into long films in MWCNTs (multi-walled carbon nanotubes). CNT thin films are used to produce touch screen appliances that replace formerly used materials like indium tin oxide (ITO). Furthermore, this technology can be used for OLEDs (organic light emitting diodes) to make screens flexible. In this Tsinghua-Foxconn case, personal relationships and trust between parties were found to be a vital element in managing such linkages between academia and industry. Most importantly, there had to be a mutual benefit and both parties had to have a need for each other.

[Insert Table 4 here]

¹ Prof. Fan Shoushan is the Director of the Tsinghua-Foxconn Nanotechnology Research Centre and he is the second highest patent holder in the nanotechnology field (398 patents).

4.3 Themescape illustration of nanotechnology linkages and clusters

In our proposed model as shown in Figure 2, it was assumed that there would be linkages within the same discipline or across disciplines, within their technological domains and their fields, and that there would be diffusion from one to the other. An examination of patents clusters shows which fields and technological domains are linked to each other. Using the Themescape mapping tool, the key technology terms are mapped for all the nanotechnology patents available (Figure 5), the density of technology terms is indicated topographically, and the distance between peaks throws light on the relationship between content as peaks that are located closer to each other have more closely related content than peaks that are located farther away. Overall, it is possible to see which domains have significant relevance within the nanotechnology field. An example is the linkage between the nanotube-nanowire polymers and the cluster of nanowire-semiconductor-optical applications, which identifies a nanoelectronics domain. By using the Themescape illustration, some of the dominant domains become very apparent and this leads to the identification of general fields such as chemical science (powders-nanoparticle-aqueous), optoelectronics (semiconductors-laser-quantum dots), biotechnology (protein-molecules-nanoparticles), and nanotools (probe-microscope-scanning). The Themescape map (Figure 5) provides support for the framework proposed in Figure 2 regarding technological linkages.

As shown in Figure 5, the technological linkages between patenting clusters and the volume of these linked patents can be seen by the contour height between each technological field. Nanotube, polymer and semiconductor terms appear together in one of the highest peaks, which indicate the dominant field of a high number of content availability within each technology and the strong relationship between them. It can be predicted that nanotubes, semiconductors and polymers have the potential to be key materials under the nanotechnology umbrella in various sectors and most importantly in the electronics field, where they increase the efficiency of materials in many ways such as by increasing the mobility and reliability of electrical properties of circuits. It has been found that random arrays of nanotubes can form semiconducting and conducting networks. Commonly, single-walled carbon nanotubes are used with polymer semiconductors in this kind of application. Some of the applicability of these materials in the industry is in display technologies, storage devices, sensors and printed electronics. At present, the scientific endeavour is to make carbon nanotubes a practical option for transistors in microprocessors and other electronics. This is one of the reasons why large establishments in the electronics industry such as Samsung, Foxconn and NEC are seriously investing in these nanomaterials, as the patents granted in this area are likely to become one of the key competitive advantages in the future.

In relation to relative applicability of nanostructures, it can be seen that nanowires and carbon nanotubes have conjoint applicability. We also looked at why nanotubes, nanowires and semiconductors appear together on the Themescape map. Nanowires are wires at nanoscale and

consequently are very thin structures. Scientists hope to use them to build tiny transistors for computer chips and other electronic devices. The characteristics of nanowires vary depending on the element that is used and they can have the properties of an insulator (e.g., SiO₂, TiO₂), a semiconductor (e.g., Si, InP, GaN) or a metal (e.g., Ni, Pt, Au). By arranging semiconductor wires in the right configuration, it is possible to create nanotransistors which can act as switches or amplifiers. Also, they can be used as logic gates (AND, OR and NOT gates) in semiconductor nanowire crossings. The nanostructures that can be made from nanowires can be used to build a nanocircuit with the help of carbon nanotubes, for example, with nanotube-based transistors (CNTFET). Yet again, this is a field in which large electronics companies are conducting research and attempting to gain key patents.

[Insert Figure 5 here]

4.4 Regional nanotechnology competencies

The data was converted to calculate regional advantages in nanotechnology as it is preferable to compare these on a relative rather than absolute basis. This transformation has been widely adopted in recent works on comparative technological developments at both country and sector level (Cantwell, 1993; Patel and Pavitt, 1997; Islam and Miyazaki, 2010). The dynamic changes in the comparative positions of different regions are identified for categorising the technological competencies of firms in the Science and Technology poles. As illustrated in Figure 6, the X-axis represents the share of patent activities in the Technology pole and the Y-axis indicates the Revealed Technological Advantage (RTA) of countries, which enables the measurement of the comparative advantage of scientific and technological strength.

The results indicate that the US maintains its high share in the Technology pole and a high RTA zone in all periods (above 40% patent share), revealing its strong competitiveness in the relevant technology field (see Figure 6). On the other hand, the Japanese position in the technology competencies moved from a high share and high RTA zone in the 1900–1994 period towards a significant low share and low RTA zone in the 2004–2009 period. The Japanese contribution in the nanotechnology field was substantial (41%), comparable to the US, in the early 1990s and then it slowly declined to around 25% in 2005–2009. This indicates that relative to other regions, the nanotechnological competencies of Japan had atrophied in the mid-2000s and have fallen behind in recent years. A similar trend was observed in the case of top European players (e.g. Germany and the UK). The decline in RTA in this case may be due to the entry of Asian rivals.

By contrast, Asian countries' trajectories are moving in the opposite direction to that of Japan and Europe. The top regional players exponentially improved their position in the early 2000s, which may

be due to their actors' initiatives and policies to push nanotechnology into potential sectors. Countries such as South Korea and China (and Russia) gained substantial strength in nanotechnological competencies in the 2004–2009 periods. Our RTA analysis indicates that the Asian giants' nanotechnology competencies have been focused on, and directed towards, the production of nanomaterials and their applications in nanotechnology-based products. It seems China is the most likely candidate for achieving parity with advanced countries. Within public infrastructures, several grassroots organisations are sprouting up to take advantage of nanotechnology. It is very interesting to see that, in their Nanotechnology pole, the development of the Asian players is exponential in nature. The analysis reveals learning patterns of technology and innovation structures for the Technology pole from a comparative evolutionary perspective.

[Insert Figure 6 here]

5 Discussion

The motivation to conduct this research is the increasing pace of nanotechnology development and diffusion worldwide. The main output of this research is in the area of nanotechnological dynamics focusing on the technology clusters and their linkages, involvement of academia's and industry's foci in terms of technological domains, and a comparison of regional competence building. In this paper, a new linkage model is proposed which assumes that this field is diffused among different technology domains, which in turn reflects the linkages within the same disciplinary fields or across disciplines. As such, the study of nanotechnological linkages has presented novel and highly informative results in terms of interrelationships within the field in comparison to previous studies. By using the Themescape tool, specific nanotechnology-related terms were analysed to identify the dominant technology clusters and to see how technology linkages are formed, their intensities and their various usages. It can be seen which domains have significant relevance within the nanotechnology field, for example, the linkage between the cluster of nanotubes-nanowires-polymers and the cluster of nanowire-semiconductor-optical applications identifies a nanoelectronics domain. Some of the dominant domains become very apparent and this leads to the identification of general fields such as chemical science (powders-nanoparticle-aqueous), optoelectronics (semiconductors-laser-quantum dots), biotechnology (protein-molecules-nanoparticles), and nanotools (probe-microscope-scanning).

The involvement of academia is found to be more dominant than corporate actors in China and Russia, as academia has been given a greater funding share. In particular, in China, a politically driven patenting system gives considerable support and motivation to academia to file patents, while corporate actors' involvement is higher than that of academia in the US, the UK, Germany and Japan, as large corporate players are located in these regions. With respect to the involvement of key actors in the nanotechnology field, the electronics industry's ownership of patents is dominated mostly by

large organisations. Also a considerable heterogeneity was found in patenting activity. There are two main reasons for this. Firstly, large organisations have the capability to provide the large investment necessary for R&D activities and they are aware of the benefits of these technologies in terms of their efficiency and for bringing about incremental innovation characteristics. Secondly, they collaborate with academic organisations, such as universities, to benefit from their inventions as well. The second point is not found in every national innovation system, but of those where there are such collaborations, for example, Korea, the US and Japan the systems appear to be the most effective.

The results also show the regional strengths and weaknesses in competence building processes. An interesting outcome of this research is that it shows that Asian players over the last few years have had a huge involvement in this area. It appears that South Korea and China are now catching up with Japan and are close to the US in terms of the number of nanotechnology patents granted. To gain an understanding of comparative dynamics, we have compared the relative technological advantages of Europe, the US and the Asian regions. This indicates that the US has maintained its leading position in the Technology pole with a high share and high RTA in all periods, revealing its strong competitiveness in the nanotechnology field. Relative to other regions, the nanotechnological competencies in Japan started losing strength in the mid-2000s and have continued to fall behind in recent years. A similar trend was observed in the case of top European players (e.g. Germany and the UK). The decline in RTA may be due to the entry of other Asian countries (especially the exponential growth of South Korean firms) into nanotechnological activities. As China has a relatively low percentage share in the Technology pole, its distinctive advantage in nanotechnology is still low, but promises to be greater in the future.

6 Conclusion

6.1 Contribution of the study

This study has discussed how this research, its methodological approach and its findings have reduced the identified gaps and improved on weaknesses in this research field. Furthermore, it points out practical and theoretical contributions to the field and reports key findings related to research objectives. Practical contributions consist of descriptive and analytical findings based on various different types of categories such as actors' performances and regions' strengths and competencies that offer specific determinants for linkage mechanisms in the nanotechnology field. The case of Tsinghua-Foxconn represents successful practice in this field, and its study has increased the depth and quality of the findings. The outcomes of this study were also found to be useful for other innovation-related collaborations. The theoretical contributions of this study are the theoretical frameworks that have been adapted and tested in this research. The technology linkage model allows the identification of technology clusters and their linkages to application or market domains.

Accordingly, this model could be adapted to different fields such as biotechnology or with other types of data such as publications.

Apart from the practical and theoretical contributions, there are also methodological contributions from this research. As explained in the research design section, this study has greater validity than other studies due to its large sample size and greater accuracy of its patent search query, which used a combination of both patent classification codes and lexical queries. Using only patent codes has a weakness in that unrelated patents appear in the patent data due to errors in their classification, but this was one of the common approaches adopted by other studies. This study offers an effective method of patent data gathering when compared to other methods and could be considered to be reliable as technological links were checked with multiple sources and supported by Themescape mapping and interview data analysis that extended the findings in the nanotechnology field.

With regard to the TEN model, networks and clusters within the nanotechnology innovation system showed that boundaries of interactions are not limited to the national level and there are interactions between different types of organisations, so it is not possible to limit this field into certain sectors. However, an identified weakness is that the linkage between the Science pole and Market pole is not strong enough in terms of innovation processes. There are some strong linkages, such as between Tsinghua-Foxconn, but these types of linkages are rare overall. The weakness in collaboration between the Science and Market poles may be why the nanotechnology field is not in its highly commercialised stage and one of the reasons can be related to its collaborative innovation process. This is because there are many radical level patented inventions that are owned by academic actors but the majority of these technologies have not yet transferred to industry.

6.2 Implications and future research

The implications of this study are the following:

- 1) The substantial increase in patent generation by Asian organisations leading to their catching up major players such as the US, especially South Korea and China, is having a great impact in the nanotechnology field.
- 2) Mapping of mature and emerging technologies within the nanotechnology field indicates future commercial applications.
- 3) Even though some nations such as the US are strongly involved in the nanotechnology field in general, it was very apparent that the key capabilities of each country and various organisations were widely divergent. This implies that nations and organisations should provide and have targeted funds and R&D to accelerate development in this field.
- 4) Governments should encourage (i.e. by funds, special policies and targeted intermediaries) their active or potentially active organisations to become involved in the nanotechnology field to gain

competitive advantage and help establish clusters or networks to adapt and develop nanotechnology rapidly.

5) Active or potentially active organisations should become involved in this field to gain competitive advantage.

6) Management in intermediaries and fund providers should focus on linking academic and industrial organisations together and the majority of funds for innovative activities should be targeted towards collaborative research.

To take this study further, there are many other relationships that could be looked at within the sub-fields of nanotechnology. Future studies could look at specific technology domains, such as nanomaterials, nanodevices and nanofabrications. As was mentioned above, there are some organisations and inventors that hold a high number of patent documents, but the question is whether they are highly influential patents in terms of citations, commercial potential and quality. Interviews and surveys collected from academic and non-academic organisations could be used to gain a more in-depth understanding of the topic. A statistical analysis of the relationships pertaining between commercialised patents and the latest patents granted could be carried out to examine various relationships between inventions and innovations.

7 References

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Table 1: The outline of research design

Patent database selection	<ul style="list-style-type: none"> • Searching for available patent database providers • Comparison of patent databases (taxonomical study) • Selecting the right patent database provider
Patent search process	<ul style="list-style-type: none"> • Analysis of patent search strategies • Gathering the right patent classification codes for nanotechnology • Choosing the required patent search terms • Eliminating duplicates by obtaining patent data with DWPI • Exporting data to TDA with TDA format
Patent data optimization	<ul style="list-style-type: none"> • Loading required fields of patent data to TDA • Filtering results to eliminate duplicates • Preparing categories and groups for analysis
Patent data analysis	<ul style="list-style-type: none"> • Analysis of nanotechnology patent data by topological mapping • Analysis of nano-technological dynamics, linkages and competencies • Comparative analysis of nanotechnology sub-categories
Results, Interpretation and conclusion	<ul style="list-style-type: none"> • Interpreting the patent analysis of technology dynamics, linkages and competencies • Discussion, Implications and Recommendations

Table 2: Actors' patent share in their respective countries

	Number of patents	25570	17168	5614	4648	2447	1243	1234	975	857
Number of patents	Countries	US	JP	KR	CN	DE	RU	FR	GB	TW
	Actors									
36351	Corporate	16599	14591	3005	973	1803	287	601	721	299
20097	Academic	8505	3730	2911	3175	548	725	612	274	520
4657	Inventors	2451	255	232	1027	214	231	31	41	59

Table 3: Actors' patent share in each technology field

	Number of patents	25714	22451	17959	13328	12923	12352	10235	9884
Number of patents	Technology fields	L Refractories, glass, ceramics, and electro(in)organics	U Semiconductors and electronic circuitry	A Polymer and plastics	V Electronic components	E Chemicals	P General	B Pharmaceuticals	S Instruments, measuring and testing
	Actors								
36351	Corporate	17568	15584	11278	9911	7567	8254	4887	5915
20097	Academic	8588	7065	6590	3731	5582	3763	4095	4122
4657	Inventors	1371	1166	1155	712	695	1141	1816	771

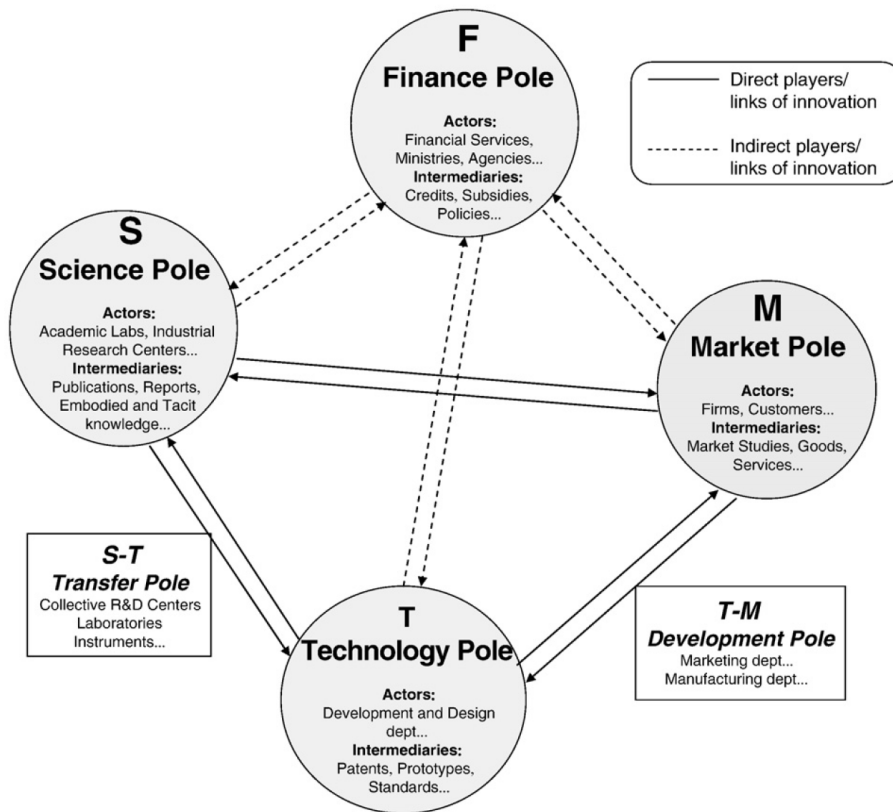


Figure 1: A modified techno-economic network (TEN) framework (Callon and Bell, 1991)

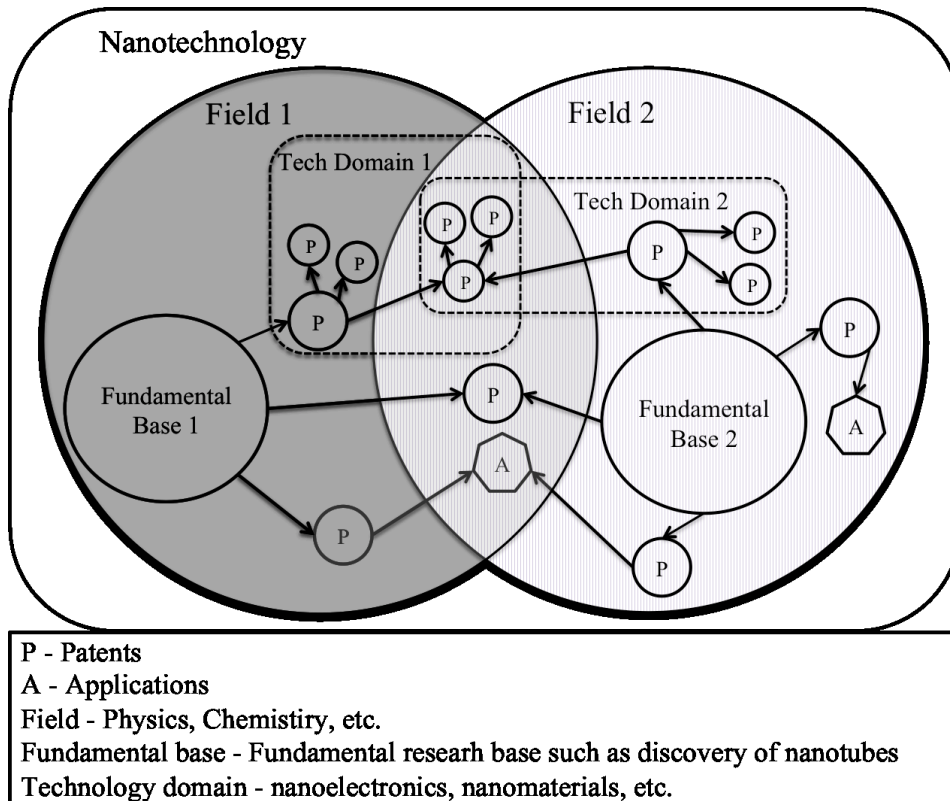


Figure 2: The proposed model of technology linkages

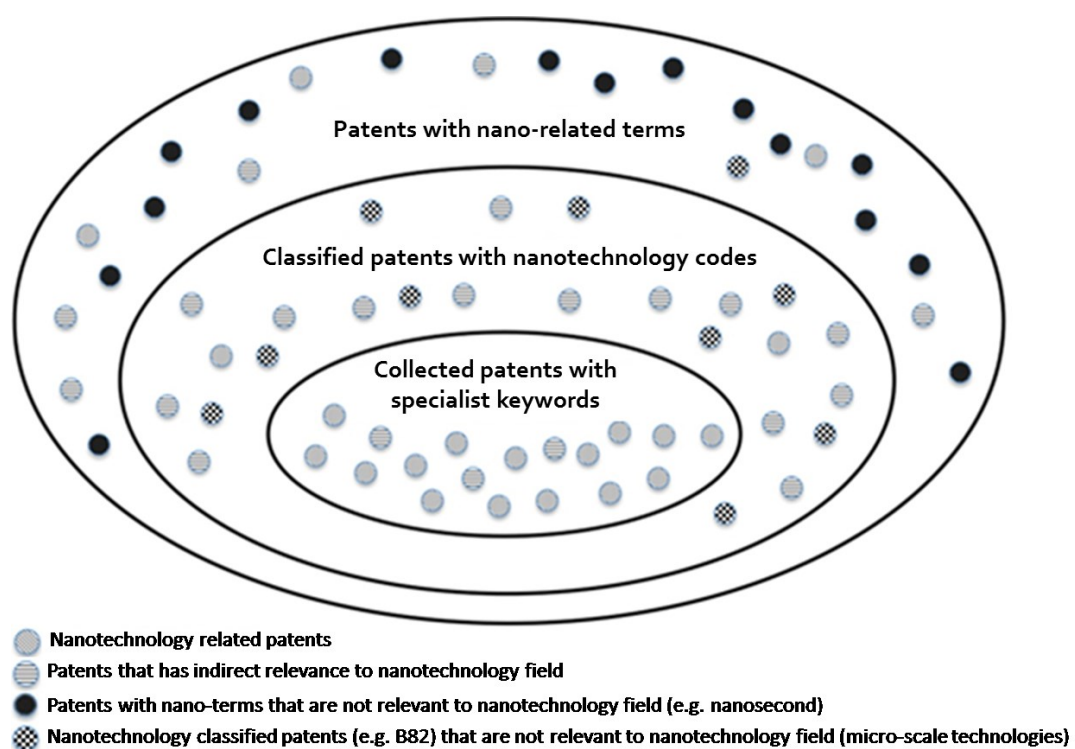


Figure 3: An illustration of patent data collection method

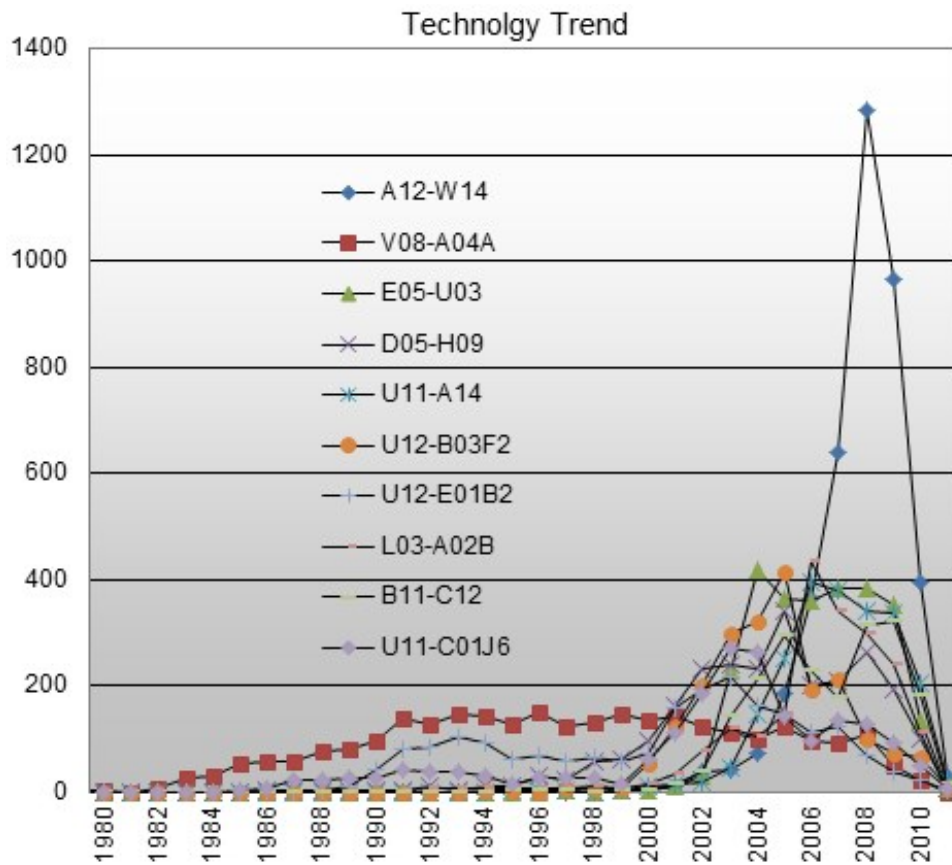


Figure 4: Development trends of technologies (emerging/mature) in nanotechnology

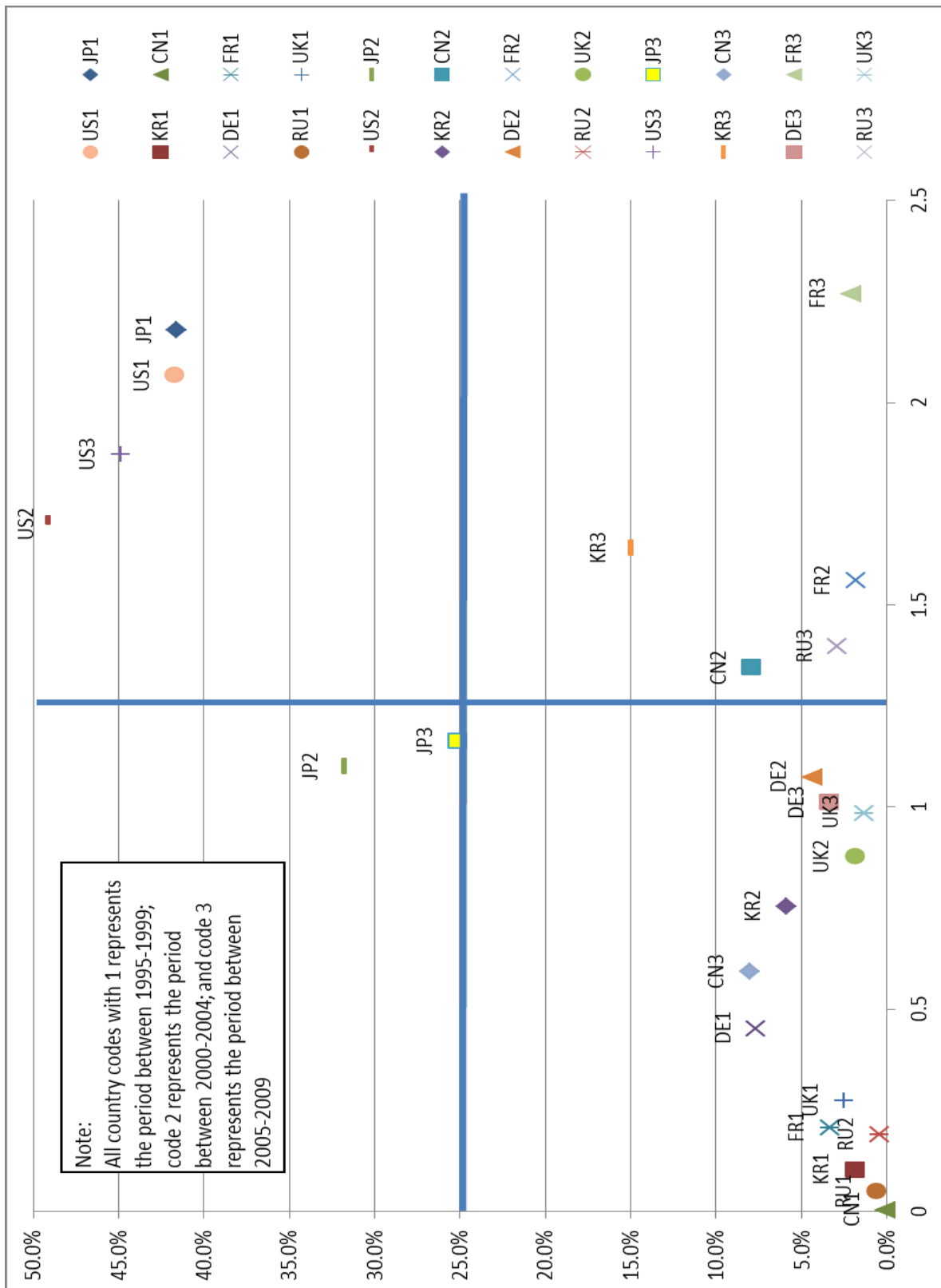


Figure 6: Profile of the regional nanotechnology competencies