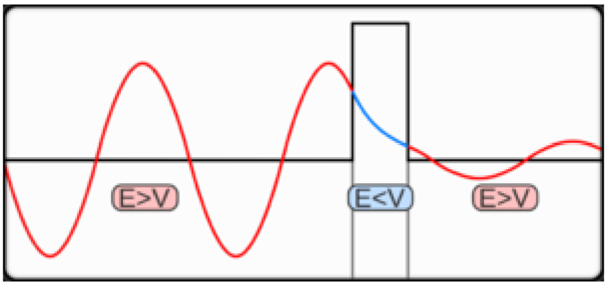
Universiteit Utrecht

Development of knowledge dynamics in the nanotechnology sector

$$-\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\Psi(x) + V(x)\Psi(x) = E\Psi(x)$$



Infinite energy will tunnel through everything

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This feeling of being lost, in a field swampy as quicksand.

Institute of building fragile foundations, using floatation devices.

Is one perpetually looking for the ever illusive former certainty.

Horrible in retrospect to find a patch of semi solidness.

Don't expect it that full of false stability.

Ever struggling to build, whilst sinking deeper.

Study through destruction, aided by many.

Here one can be helped only by one.

Infinite energy will tunnel through everything

The world of quantum mechanics is magic coming to life. An example often given of the Heisenberg principle of uncertainty is the infamous Schrodingers cat in the box. Besides this example there are many more odd aspects to quantum mechanics. One interesting feature is quantum tunneling, which very basically states that a quantum particle is able to tunnel through material depending on the energy it has, without interaction with the surrounding material. This behavior is dictated by the ever present Schrodinger equation. The entangled nature of this thesis with both the realm of quantum mechanics through nanotechnology and its relation to uncertainty through institutionalized procedures or the lack thereof is p(a)<oe>t(het)ic.

Abstract

This research aims to come to an understanding of the knowledge dynamics of the relatively 'new' scientific discipline: Nanotechnology. Hereby this research makes use of a recent developed approach by Bonaccorsi (2004; 2007; 2008) which is known as 'search regime'. A search regime is used to explain the knowledge dynamics of sciences. One of the main propositions made in this research is that the characteristic of a specific search regime applicable to nanotechnology can help to explain the geographical dynamic networks in the field of nanotechnology. The main question of research that is investigated:

What are the characteristics of the nanotech search regime in the 1996 to 2011 period?

This question has been split up into three sub questions of research:

How has the volume of knowledge dynamics developed and what are the main contributing regions?

How do topics of nanotech knowledge production diversify and what departments are most relevant?

What combination of active organizations is most predominant in the development of knowledge dynamics of the sector?

In order to investigate these research questions this research makes use of the search engine: Web of Science. Downloaded publication data for 1996-2011 in the field of nanotechnology are organized in databases created in Microsoft Excel and Access in order to conduct the analyzes at the micro level. Aggregated publication data forms the basis for several numerical analyses based on the different properties. Analytical software used are ISI.exe, Cities.exe.

The volume of knowledge production increased substantially until the year 2008 when it stabilized. The topics of knowledge production increasingly diversified from the year 2000 to 2006. The departments active in the field increasingly diversified over the timeframe of interest. The knowledge production utilizes international cooperation with stability. The actors active in the field stabilized with a strong focus on universities for knowledge production. Geographically speaking the field of nanotechnologies has been stabilizing since the year 2006. The field is mainly concentrated in East Asia. Content wise the field of nanotech shows differentiation in disciplines producing a stable fraction of topics. The actors in the field are dominated by university input.

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1. Introduction

1.1 The new science of nanotech

The need for knowledge intensive innovation is especially relevant for rapidly developing scientific disciplines, since their inherent undeveloped state of research will yield new insights. Rapidly growing and diversifying scientific disciplines are referred to as "new sciences", and they are likely to branch into new subjects (Bonaccorsi, 2008). These new sciences progress rapidly as a result of more actors being involved and are greatly influenced by the availability of novel technology. In particular, information and communications technologies have amplified the opportunities to share knowledge and decreased the time of information transfer (Skinner 1995; Wagner 1998).

Nanotech is one such promising new science, experiencing rapid growth, divergent dynamics, and new complementarities, which are all aspects of new sciences. One of the earliest conceptualizations of the field of nanotech was a lecture given by renowned physicist Richard Feynman presented at the American Physical Society meeting. On December 29, 1959 he gave a lecture at Caltech titled: "There's Plenty of Room at the Bottom." In this lecture Feynman considered the possibility of: "Direct manipulation of individual atoms". This was principally the basics of the field of nanotech and this is considered to be a seminal event in its history. Furthermore Feynman continued with his train of thought to suggest that it would be possible to "arrange the atoms the way we want". This would possible lead to the fabrication of devices on a nano scale. This industry is knowledge-intensive and paves the way to work with particles in the order of magnitude of nanometers (nm), which is one-billionth of a meter. This is a scale of size just above that of atoms 0.060 nm to 0.275 nm, and is in the range of simple molecules. The basic idea behind nanotech is that it should be possible to use atom-sized particles as building blocks to construct complex structures. Practical application can be found in the further miniaturization of electronic chip technology, giving rise to new materials, downsizing solar cells or creating devices to be made at the molecular level.

1.2 The relevance of nanotech

Nanotech is important because it will provide sustainable economic development in the future, through the generation of new scientific knowledge. This significance is reflected in the receiving of extensive investments from both the public and private sectors. An example of this is given by the European Union (EU), which is focused on stimulating knowledge development of nanotech. In the estimate of the EU Commission, nanotech may become a leading field of science, industry and employment over the coming decades. The development of nanotech will result in increased prosperity and creates not only more, but better jobs (Commission European Communities, 2005). Nanotech has preferential status for stimulus measures, such as access to special grants. The EU set up the Sixth Framework Program for Research (FP6), focusing on innovative sectors, new sciences and international cooperation. The program has set aside €17.5 billion aimed at promoting international collaboration and cooperation between target countries (Commission European Communities, 2004). This program is stimulating the translation of scientific advances into marketable innovations in a generic character, where all sciences will be stimulated along similar lines.

The economic influence of countries and regions is attained through the sustainable development of the regions activities over time. Bettencourt claims that "for the sustainable development of society, continuous growth of knowledge and innovation are required to avoid stagnation or crisis" (2006). As a knowledge intensive field the inventive activities of nanotechnologies have risen substantially since the end of the 1990s (OECD, 2009). This trend is making the nanotech field an important potential future economic driver and therefore of interest for the sustainable development of society. A growing number of countries are contributing toward the global scientific development, intensifying the competition in knowledge production, making specific stimulation of fields such as nanotech increasingly more important.

1.3 The European paradox

Knowledge is seen as one of the most important aspects of economic development and growth (OECD, 1996). Nations have focused resources on stimulating knowledge intensive industries, yielding implications for stimulus policy (Wagner and Leydesdorff, 2005). The relationship between knowledge and economic development is not entirely clear. This relationship can be seen as the translation of knowledge to economic gain. An example of the lack of understanding is given by the fact that European science is quantitatively comparable to the US, but paradoxically Europe's technological position is much weaker. The comparative failure at capitalizing on knowledge is labeled the 'European paradox' (European Commission, 1995). Besides the differences between the US and Europe, there are also differences between the European nations for capitalizing on knowledge. Bonaccorsi states that these negative differences could maintain or widen the gap between rich and poor European regions. This will result in brain drain, disintegration in science systems and create a highly polarized Europe, with a negative effect on the democratization process on the European continent (2012).

The need for advancing the capitalizing on knowledge through knowledge intensive innovation will have to be balanced with the problem of enhancing social differences within Europe. This is a complicated political challenge of the near future and will require specific legislative action based on a predictive quantitative theory (Bettencourt, 2007). Bonaccorsi portrays a similar view by proposing that legislation will require a large-scale analysis of the innovation systems and their knowledge dynamics (2007).

In his analysis of the European paradox Bonnacorsi challenges the notion that "competitiveness problems of Europe are rooted in the relative inefficiency in transforming good scientific knowledge into commercial applications." In his views European sciences are not as strong in the most competitive fast moving new fields. Also fields characterized by divergent growth are less rooted in Europe, many of these sciences are at the core of breakthrough technological developments (2007).

1.4 Similar research

A study that has focused on analyzing new sciences such as nanotech, have been executed by Bonaccorsi who developed the concept of a 'search regime', a set of abstract dynamic properties of a specific scientific discipline (2008). Part of the search regime is the way in which scientists generate and spread their work, which is referred to as 'knowledge dynamics'. This may involve the identification, integration, sharing, application and evaluation of information or knowledge (Bonaccorsi, 2004). A knowledge-intensive sector is defined as a field in which the production of knowledge has a dominant role. The knowledge dynamics are sector-dependent, meaning that nanotech has its own knowledge dynamics. Sector dependent knowledge dynamics will need to be researched in order to understand the workings of the field. The knowledge dynamics of the nanotech sector are developed over time by the dynamic interplay of actors. The interaction between organizations, such as corporations, knowledge institutes and governments, and individuals are considered to be a cooperative interaction, with a self-enhancing aspect that is referred to as evolutionary (Boschma and Martins, 2010).

A descriptive study into analyzing new sciences such as the knowledge production of the biotechnology field was performed by Heimeriks and Boschma (2012). This preceding empirical study of new sciences has been focused specifically on the evolution of knowledge in major biotech journals to identify emergent subjects within the field. In this thesis the approach and methodology of Heimeriks and Boschma will be used for the rapidly developing field of nanotechnology, since this field has not yet been investigated. The similar approach of this thesis will be recognizable in the research questions of this study. For the former a further focus on the results of Heimeriks and Boschma is required. The study found that biotech knowledge production is geographically concentrated with many newcomers to the field from Asia. Heimeriks and Boschma make a distinction between areas based on their population growth. Where high growth areas tend to develop new topics that are rapidly growing and more promising, potentially yielding larger returns and more suitable to create sustainable fields of research. This is in contrast to slow growth areas, which were more associated with topics that lost importance in the scientific field of biotech. Heimeriks and Boschma state that fast growing areas create more promising subjects. The rapid growth will provide more opportunities for newcomers since legislative stimulation in favor of the field is tailored to this purpose. These conclusions have led to the formulation of the research question analyzing the development in the search regime of the nanotech field.

1.5 Research question

The main question of research addressed in this thesis is of a descriptive nature, by investigating and describing the knowledge dynamics of the field of nanotech over time. This description aims to identify trends that can provide insight for future legislative purposes. Therefore the main research question of this thesis is the following:

What are the characteristics of the nanotech search regime in the 1996 to 2011 period?

In order to answer this research question, a split has been made in order to make the question researchable. The main question has been divided into multiple sub-research questions.

The first characterization is related to the absolute development and spatial distribution of knowledge production within the field of nanotech. The volume and locations contributing the largest amount of knowledge production will be quantified over time, leading to the first sub question on the geographic development of the field of nanotech:

1. How has the volume of knowledge dynamics developed and what are the main contributing regions?

Another characterization of knowledge production is related to the direction of research within the field of nanotech. This direction will investigate into the nature and continuity of knowledge production within the field of nanotech. The different topics will therefore be identified and analyzed for continuity; this has developed into the second sub question on the content development of the field of nanotech:

2. How do topics of nanotech knowledge production diversify and what departments are most relevant?

The last characterization addresses the source of knowledge production in the nanotech field. The contributing actors that produce the most knowledge will be identified. This has led to the third sub question when answering on the actor development of the field of nanotech:

3. How does international cooperation develop and what combination of actors is most predominant in the development of knowledge dynamics of the sector?

1.6 Relevancy of research

This research offer insights into the historical development of the field of nanotech up until its current state. This is vital for governmental stimulus of the field as clustering phenomena such as powerful productivity advantages, economies of scale and knowledge spillovers that such density brings (Florida, 2005). National governments often develop policies in order to benefit both economically as well as in prestige. The European Commission also envisions scientific links across borders when attributing these policies (Leydesdorff and Persson, 2009). In order to stimulate the field of nanotech strong geographic clusters need to be generated with potentially cross border cooperation's. The problem with geographic specialization of knowledge production being a strong driver of economic growth is the difficulty of identifying the correct field of future specialization. Regions cannot do everything in science, technology and innovation.

In the past policies has been developed on the idea of "best practice models" these were based on well performing areas and high-tech regions. The best practice is not specialized to a situation, but rather applied in a similar way across many types of regions. Tödtling and Tripp show that there is no "ideal model" for innovation policy as innovation activities differs strongly, requiring specific research (Tödtling, Tripp 2005). One important aspect is that an explicit cluster strategy was found to be crucial step (Cooke, 2002; Todtling, 2002).

This makes it a relevant policy action to initially identify newly emerging regional complexes of related industries, these preferably have a strong local knowledge base in the region. For such situations it will be important to stimulate their growth and dynamic development (2005, Tödtling, Tripp).

Dominique Foray claims that for useful governmental stimulus, a focus on a specific knowledge base is needed within scientific disciplines. Therefore, as Dominique Foray explains, they need to focus on a knowledge base that will make them unique. In other words, regions need to specialize in a smart manner. It is vital to specialize in order to utilize the potential for scale in a knowledge domain, since large-scale activity creates spillovers in knowledge production. Identifying specific fields of knowledge within nanotech is not a simple task and requires considering the context of the field of research. An analysis that has taken the context into account will allow for "smart specialization" departing from the generic measures in use today. The exchange of ideas among individuals is considered a spillover and can be an important driver of contributing productivity of R&D and other innovation-related activities (D.Foray, P.A.David & B.H.Hall, 2011). Successfully identifying a domain requires taking into account both the context and any specific conditions. This specialized approach will create multiple lines of regional and national specialization that are sustainably profitable for fields such as nanotech (D.Foray, P.A.David & B.H.Hall, 2011). The analysis of this thesis into the field of nanotech is relevant since it creates a critical technology survey allowing for technology foresight.

1.7 Following chapters

This thesis will characterize the knowledge production of the nanotech field and attempt to discern trends and is structured into six parts. In this chapter the introduction was presented together with the research questions. In the next chapter, the theoretical framework will be discussed, introducing hypotheses related to previous research. Subsequently in chapter three, the theory will be operationalized. In chapter four the methodology for testing these hypotheses will be presented. This chapter will describe what data is required, how it will be gathered and processed for this analysis. In the fifth chapter the results are displayed and discussed. In the sixth chapter the results will be utilized in order to answer the questions of research. Finally the entire research and its choices will be discussed in the last chapter.

2. Theoretical framework

This thesis aims to determine the characteristics of knowledge dynamics in the nanotech field by dimensions of importance. These dimensions will be defined from the findings of others and will be used to formulate hypotheses for each of the research questions. Three general fields of preceding studies will be discussed. The current chapter begins with Bonacorssi's search regime on knowledge production. Next the theory on general characteristics and the geography of knowledge production of the nanotech sector will be discussed. Thirdly, the content development of knowledge production and its relation to the evolutionary perspective will be presented. Finally, this chapter will address the development of actors and their cooperative nature.

2.1 New science

In the second half of the 20th century science evolved from classical science into what is previously referred to as new science. There are a few aspects that have led the development of these new sciences, these aspects structure environment where scientists work and generate their knowledge production. The initial development achieved changing and evolving science was decrease between prediction, observation and manipulation. Where for new sciences the theoretical prediction is often postulated before the empirical observation has actually been made, this is often caused by the limitations provided of the available experimental technology (Galison, 1997).

The discrepancy between observation and manipulation in scientific developments that existed in classical science has changed through breakthroughs in scientific equipment and the rise of an independent instrumentation industry. A focused push was made to design and manufacture Equipment that would provide observation that could explain theorized effects, this trend aided in the conception of new sciences and the (Bonaccorsi, 2008; 2004). The development and production of instruments used in experiments has become a field of science in itself (Zucker and Darby, 2003). This can for instance be seen in the field of nanotech in the form of the scanning tunneling microscope or the pulsed laser deposition technology.

Besides specific experimentation equipment the development computer technology had major impact on the scientific community. This complimentary field of science has been most useful in reducing the effort it takes for knowledge to be transferred, or as Bonaccorsi states: “The increase in computing power is a radically new factor in science” (2008). This continuous increase in computer power has for instance lowered the costs of simulating real life scenarios, making it possible the tests specifically designed situations without producing them physically. The computer science development has gone hand in hand with the field of mathematics, continuously generating new algorithms that achieve better results in computer simulations (Skinner 1995; Wagner 1998). Besides the ability of better simulations another important aspect of computer science is the possibility to accelerate the integration of different scientific fields. This allows scientists to be cognitively more compatible with different levels of research from the same discipline or different disciplines.

This has led to the formulation of a few aspects of new sciences by Bonaccorsi, new science grows very rapidly this is caused by a large flow of entrants in new fields. This can be identified when one investigates into the in published output (2008). Besides this rapid growth new sciences grow more diverse, this is caused by new theories that often occur in new fields through the synergy of knowledge from existing fields. These new theories generate an diversification of new fields of research through competing sub-theories (2008). New forms of complementarity due to required Actors in the field of research will develop similar abilities allowing them to interact and cooperate with other actors at different institutional levels (2008).

2.2 Sectoral system of innovation

Knowledge development and innovation is a process involving different cooperating actors. Actors such as firms do not innovate without cooperation making innovation a collective process (Lundvall, 1993). These actors cooperating in the innovative process will interact with "other firms as well as with non-firms organizations such as universities, research centers, government agencies, financial institutions" (Carlsson, 1995). This insight generates attention for the interdisciplinary nature of knowledge development (Edquist, 1997).

A multidimensional, integrated and dynamic view of sectors is provided by Malerba through the concept of sectoral system of innovation and production. In his description of the sectoral system of innovation Malerba states it is "a group of agents are individuals and organizations at various levels of aggregation, with specific learning processes, competencies, organizational structure, beliefs, objectives and behaviors." The actors in the sector share a knowledge base, with technologies, inputs and demand. The actors interact through "processes of communication, exchange, co-operation, competition and command, and their interactions are shaped by institutions." The sector of nanotechnology is very compatible with the model proposed by Malerba (2002).

2.3 Search regime

In order to analyze the innovation system of the nanotech sector, the knowledge dynamics of organizations and individuals within the field are evaluated. The approach of Bonnacorsi will be used in order to do this, Bonnacorsi utilizes a practical model of innovation systems based on similar ideas as presented by Malerba. This involves determining and analyzing the set of cultural or social norms and rules involved in the interaction of organizations and individuals. The social and cultural rules regulate the operation and interactions between different organizations and individuals and are considered to be the "regime" of interaction. Organizations and individuals active in a regime are considered actors. The performance of a specific field is therefore analyzed by investigating the regime's actors and associated environmental properties (Bonaccorsi, 2004).

The set of abstract dynamic properties described as a regime is referred to as a "search regime" when it is related to a specific scientific discipline aimed at knowledge dynamics (Bonaccorsi, 2008). The term "search regime" describes the nature of the interaction between participants within any scientific discipline. In other words, the search regime is the characterization of the interplay between the actors. Within a scientific discipline, the search regime describes the way in which knowledge is produced and shared in that field. Knowledge is shared when participants interact. Interactions are constantly evolving as participants conduct, expand or restructure their research.
The nature of each search regime is unique since the structural properties differ between disciplines.

Additionally, search regimes vary as a function of the resources used, organizations formed and theoretical models utilized. Approaching the analysis of a scientific field from a search regime perspective utilizes a framework where the research process of scientists can be explored. This is done by describing the characteristics that work best in their specific geographical regions (Bonaccorsi, 2007). The search process, or the way in which scientists tend to generate and spread their work, is referred to as "knowledge dynamics" (Bonaccorsi, 2004). The knowledge dynamics are considered a structural property of the search regime. The knowledge dynamics of the search regime are specific for the field of research the scientists are active in (Bonaccorsi, 2004).

A dynamic search regime can develop with a pattern, this can be either a convergent or a divergent pattern. A convergent search regime develops knowledge production along a generally accepted theory. This makes it unsuitable for new entrants into the field of research and makes it harder for new scientists add their own new theoretical propositions.
A divergent pattern is characterized by incorporating and creating new fields of research. For a new science such as the field of nanotech the expectation is that the growth pattern splays a divers behavior (Collins, 2003). This divergent pattern is associated with being exposed to an increasing number of different scientific fields through time creating further diversification. When the diversity is stronger more influences from other fields scientific development will be incorporated, this will raise the level of the research within the field (Bonaccorsi, 2008). From this the expectation is drawn that areas subjected to a divergent pattern of scientific knowledge production are attracting more entrance of new fields than regions showing a convergent pattern (Bonaccorsi, 2004; 2007; 2008).

2.4 Geographic development

An important aspect in the development of the nanotech search regime is the location of knowledge production. The specific location is important because it influences how actors evolved. Analyzing actors evolving in different geographic locations is an evolutionary geographic approach. Patterns are produced over time from the co-evolutional development of actors, where the geographic spread of economic activity in the present is a result of past events making it path dependent. This is phrased by Dosi as "The explanation to why something exists intimately rests on how it became what it is" (Dosi, 1997).

The path dependent development of a sector describes how the science has evolved. Therefore the first sub question aims to characterize the absolute development and spatial distribution of knowledge production within the field of nanotech over time. The volume and locations contributing strongest to the knowledge production will be quantified over time. This can be measured both in the number of new actors in the network and as the quantity of scientific output in the form of publications (Bonaccorsi, 2004). Rapid progress is expected for the field of new sciences and will continue to "create new fields of research at high pace even in their maturity" (Collins et al, 2003, Luscombe, 2001). Science can develop through two distinct patterns, a convergent pattern where research develops in a streamlined manner. The research is producing knowledge that is complimentary to a paradigm. The other option is a divergent pattern where research diversifies into different directions creating new fields and new research areas, new sciences grows very diverse (Collins et al, 2003). The development of new scientific areas will create growth of knowledge production that is exponential for the scientific field (Bonaccorsi, 2008). This will lead to the creation of entire new subfields related to the field of nanotech.

The associated knowledge production is expected to increase dramatically. This will be a self-enhancing effect, attracting new actors to the network, caused by new actors expecting that fast growth will accommodate their addition (Bonaccorsi, 2008). There is a significant relationship between the amount of knowledge produced and the number of actors in the network (Lanjouw and Schankerman, 2004). An increase in the number of actors will create greater competition, improving the quality of the knowledge being generated (Bonaccorsi, 2007). Adding to the self-enhancing effect is that scientists at the highest echelon often want to be involved in the most cutting-edge research; these scientists desire to participate in order to minimize their opportunity costs, since increased proximity has structural advantages (Bonaccorsi, 2007). By the reasoning of path dependency, geographic regions with an established history of nanotech will display greater proliferation. Path dependent progress is expected to generate a growth of actors, as well as cause the actors to be more active within the network, making the first hypothesis:

Knowledge production within the nanotech network has increased.

The uneven spatial distribution of scientists is also a consequence of path dependency (Bonaccorsi, 2004). The path dependency concept states that the interaction between an actor and its environment is influenced in its outcome by their history of interaction (Boschma, 2004). This effect is self-reinforcing and therefore makes economic uneven geographic distributions also create path dependent environments (Martin, 1999). The spatial dynamics between actors and environment involve regional leadership. When this interaction has been established, it will be very difficult to change (Boschma, 2006). The clustering, or spatial concentration, described by Florida is a concept of increasing density of organizations and/or individuals in a given path dependent environment. This is an evolutionary consequence of path dependent clustering that involves positive spillovers (Klepper, 2002). Since knowledge accumulates in locations and does not spread easily, Heimeriks and Boschma argue that existing scientific knowledge provides building blocks for further knowledge production. Making the production of scientific knowledge a cumulative and path-dependent process related to specific region (2013). Spillover of knowledge dynamics between actors in the nanotech field manifests itself in the spinoff of firms and labor mobility (Maskell, 2001; Essletzbichler and Rigby, 2007). The copying of successful routines related to knowledge dynamics happens in a fixed geographic location (Klepper, 2007). Since these routines will be copied based on their success, the successful routines are more likely to spread to other local firms, creating a spatial evolution of firm-specific routines in a geographic location. Through success of routines, the process of economic development is a place-dependent process (Martin and Sunley, 2006). These aspects of interactive knowledge production show that it is important that actors work together in close distance. Therefore an aspect of knowledge development is that geographical proximity to crucial knowledge is important (Sorenson et al. 2006). Actors are expected to be driven together creating dense areas of interaction, therefore in hypothesis 2 it is expected that:

The actors involved in knowledge production are spatially concentrated in a few regions of importance.

2.5 Content development

The nature and continuity of knowledge production within the field of nanotech is investigated in the second sub question. Different topics will be identified and analyzed for continuity of knowledge development. The development of knowledge in a search regime can progress in two ways: convergent or divergent, this can be identified when one researches the dynamic aspects of a search regime. In convergent progression, knowledge production is in line with a generally-accepted common paradigm. A divergent progression occurs when knowledge is developed without this paradigm; it generally involves the creation of new subfields and is common in new science (Collins et al., 2003).

Nanotech has a multitude of practical applications, it is likely to expand and engender new fields research. This type of development is congruent with divergent progression, which brings about increased variety. Increased variety leads to an improved quality of knowledge production; the addition of new points of view is likely to generate better insight (Bonaccorsi, 2008). New sciences are increasingly multi- and interdisciplinary (Gibbons et al., 1994). Therefore, geographically distinct areas active in new science will be more likely to generate science with a divergent progression. Areas active in other scientific field are expected to show a convergent progression. For the field of nanotech, the development of knowledge is expected to diversify, which has led to the following third hypothesis:

Topics in the nanotech knowledge production develop increasingly divergent.

In order to develop knowledge, scientists require various resources, which may include specific instruments, laboratories and IT capabilities. A difficulty many scientists face is acquiring necessary resources, including funds and guidance. When scientists use similar resources, it is called “technical complementarity”. The extent to which an actor in a network depends on resources can be assessed. This dependency will be dependent on the specific geographical region (Bonaccorsi 2004). As scientific discipline’s dependency increases, path dependent behavior will become more dominant (Bonaccorsi, 2007).

New science relies upon a greater number of resources compared to old science (Luscombe, 2001). The application of resources in nanotech is often exclusive to its specific search regimes. As the field grows and a greater number of resources are used, variation of the types of resources increases as well. As a result, the actor’s dependency on these facilities will be divided over a variety of resources; in other words, actors become less dependent on specific resources.

Consistent environments are considered to be more path dependent compared to unstable environments. Path dependency causes stable environments to experience a development pattern with a lower growth rate in comparison with an unstable environment (Bonaccorsi, 2007). The regions with a high variety of resources and low dependency will have strong growth of knowledge production. Conversely, regions with low variety and high dependency will have weaker knowledge production growth, this has led to the fourth hypothesis:

The nanotech network’s knowledge production utilizes increasingly diverse resources.

2.6 Actor development

The actors contributing to the production of knowledge to the field of nanotech is analyzed. The actors are the source of knowledge production in the field and therefore the key players. Innovation related to enhancing interaction and cooperation has influenced the competition between organizations and individuals. Organizations competing in a sector are dependent on a competitive advantage in a sector. “Competitive advantage” is defined as the strategic advantage one entity has over its rival entities within its competitive environment (Porter, 1998). One way of improving that capacity for competition is through geographical specialization of knowledge. In a competitive market, the competitive advantage of an actor or organization is enhanced by superior geographical positioning.

Clustering of organizations as described by Klepper makes it apparent that there is a path dependent component in relation to the location of economic development (2002). The clustering of economic activity can happen with different types at many geographical levels, forming a complex system embedded in a larger economy (Fujita and Krugman, 2004). For the transfer of knowledge the distance between actors is of influence as it is not easy to transfer knowledge geographically (Gertler, 2003). It is difficult to share knowledge effectively between individuals and organizations. This difficulty aids to location dependent behavior of knowledge, making knowledge accumulate geographically fixed. When being geographically close in the process of knowledge production, actors build upon and augment each other’s research within a network. This is referred to as “cognitive complementarity”. Networks have different combinations of competent actors, each bringing a unique background and environment, and impacting the quality of the research (Bonaccorsi, 2008). Actors in a search regime require cooperation with other actors in order to share their diverse abilities, creating new ideas (Bonaccorsi, 2007). Moreover, actors may relocation necessary to cooperate with other actors when they are faced with rising opportunity costs. Therefore actors in a developing science can experience a desire to become more complementary in a cognitive sense. This will compel their relocation when the desire becomes strong enough (Bonaccorsi, 2007). The amount of collaboration among researchers of knowledge-intensive subjects is increasing. Collaborative research in geographically proximate countries increases the likelihood of scholarly co-authorship. This leads to internationally cooperating research hubs, where scientific institutes collaborate and compete with one another (Wagner and Leydesdorff, 2005). In established fields, where the regime has become convergent, actors will spend more time in proximity with one another. As stated previously, the field of nanotech is expected to be divergent in its knowledge production. The actors will be involved in increasingly global activities to access different resources for advancement leading to the following fifth hypothesis:

The nanotech network is increasingly producing scientific knowledge though international collaboration.

A successful knowledge development asks for compatibility of institutions and their environment. This is called the “institutional complementarity”. Institutes can be of a multitude of organizational backgrounds and fields; nanotech actors have been known to collaborate with parties such as governmental institutes, material laboratories and semiconductor industries. Frequent interaction between universities and institutes is necessary to aid the development of the scientific discipline

(Luscombe, 2001). When an actor's research involves practical application, they may establish strong complementary relationships with institutes having aligned goals. This complementary relationship can be beneficial for institutions allowing them to seize opportunities provided by new industries and enable the revival of mature industries, (Martin, 2010) it is expected that the cooperation between scientists and industry within the nanotech field will become more important, leading to the generation of more practical applications. This reasoning has led to the formulation of the following sixth hypothesis:

The nanotech actors display increasing collaboration between commercial organizations and universities for the production of knowledge in the form of publications.

3. Operationalization

For measuring and influencing the results of policy, science and technology indicators (STI) have been developed and are used by researchers in technology policy studies and documents. The Organization for Economic Co-operation and Development (OECD) developed these science and technology indicators, in order to investigate the technological development (Godin, 2003). Or as the American based National Science Foundation states: “The goal of science and technology indicators is to reveal the strengths and weaknesses of US science and technology, in terms of the capacity and performance of the enterprise in contributing to national objectives” (Godin, 2003).

Science and technology studies in industrial nations are performed by measuring quantitative data. The use of these indicators has led university researchers to develop the scientific fields of scientometrics and bibliometrics (Godin, 2003). By using statistics STI data is processed and analyzed, since this is the most suitable mathematical tool for the treatment of numerical data on social phenomena (Godin, 2003). A suitable tool to understand the processes that determine the productivity of authors and inventors in new technology is the counts of articles (,Zucker et al., 1998, Zucker et al., 2002).

The environment of scientific knowledge development and execution of research is also referred to as the scientific “search regime”. Development of search regimes can vary in growth rate and the extent of divergence. Therefore scientific search regimes can develop differently while co-evolving within similar socio-economic environments (Heimeriks, Leydesdorff, 2011).

For policy makers working on the creation and stimulation of knowledge-based economic activities, the understanding of search regime development is of vital importance (Heimeriks and Leydesdorff 2011). Copying scientific knowledge or scientific research is unlikely to be successful since knowledge is not fully tacit, and will be incomplete when copied (Collins, 1985). Therefore policy needs to be tuned to the specific situation.

Each scientific field and its related institutes will react differently to governmental influence, and a one-size-fit- all approach to knowledge development stimulating policy is insufficient. In order to understand the difference in co-evolution of search regimes and reaction to stimulating policy measures, the development of search regimes must first be mapped (Heimeriks and Leydesdorff, 2011).

To test the hypotheses, the properties of the nanotech search regime have been operationalized. The variables used for testing the hypotheses are based on analyzing journal publications, for this the method of Leydesdorff and Persson is used (2009). In the first three paragraphs of this chapter the variables related to the three sub questions will be introduced. In order to execute a quantitative analysis of nanotech knowledge dynamics over time the data for the variables should be acquired, which will be described in paragraph four.

3.1 Geographic development

In order to test the first two hypotheses, three indicators will be described. The progress of knowledge dynamics can be measured by analyzing the development of absolute knowledge production over time. The **number of publications** produced can be used as an indication of how knowledge production has developed. The actors involved in the production of publications describe the progression of knowledge dynamics. Progression is described by the absolute **number of actors** producing involved in producing knowledge in the field of nanotech.

The field of nanotech is active in different countries therefore the international geographical distribution is necessary to be analyzed. The **number of countries** and the **number of cities** producing publications is used as an indicator. In order to create an overview of the global distribution of active cities, the continental activity has been analyzed. The performance of continents on their **number of top cities** producing publications is used as an indicator.

3.2 Content development

The required resources of network actors who produce knowledge are analyzed in the technical complementarity. That entails includes different organizations in the direct environment of the actor. The creation and distribution of knowledge, conducted through the actors' interaction with their network, are important for analyzing the knowledge dynamics (Nonaka, 1994). Path dependency is a consequence of actor cooperation within a network (Bonaccorsi 2008). Therefore, the **topics of publications** produced by actors in the network in order to create the knowledge dynamics are important.

The direction of progression will show whether the field tends to diverge or converge. When a network becomes more diversified, it will branch out into other disciplines. This means that the field is inter-disciplinary, since it uses many disciplinary approaches by acquiring them externally from other fields. Conversely, concentration is when the interaction with other disciplines decreases. This means that the field is multi-disciplinary, since it uses many disciplinary approaches without having to acquire them externally. The relation of different disciplines active in research can indicate multi disciplinarily. The number of **department** active in producing scientific knowledge is an indicator.

3.3 Actor development

To acquire capabilities, like new techniques or procedures, an actor must be exposed to other disciplines and information. Through the interaction with other actors, new combinations will be generated, therefore the fraction of **cooperation in publication** is of interest. It is also possible for actors to interact with other disciplines and result in the generation of new combinations (Glanzel and Schuberi, 2001).

Groups of actors in the network cooperating outside their specializations describe the complementarity of institutions. This happens when actors of more than two disciplines are active. This kind of interaction has been described by the Triple Helix model, indicating that there are primarily three groups of actors active in cooperation: governmental institutions, industrial institutions and educational institutions (Benner and Sandstorm, 2000). The distribution of different **organizations** in knowledge generation in the field of nanotech is of interest.

Moodysson & Jonsson state that a “relational proximity” is necessary for collaboration between the actors involved in knowledge production. Collaboration between actors is mainly dependent on coordination and less on joint problem solving. In this cooperation the functional distance can be bridged and communication can be handled at a distance. The “relational proximity” is based on compatibility such as a shared educational and/or professional background, this helps to generate trust in professional skills of cooperating actors (Moodysson & Jonsson, 2007).

4. Methodology

4.1 Data acquisition

The setup of this thesis is the testing of hypotheses, these hypotheses have been derived from the search regime approach. For the testing of these hypotheses a bibliometric quantitative research has been executed. Therefore the function of this case study is hypothesis testing (Yin, 2003:p.19-20). This research will utilize publication data derived from a specific renowned scientific journal, namely the journal Nanotechnology. All publications in this journal and within the 15 year period of interest from January 1997 to December 2011 will be acquired. The particular time delimitation was chosen since the journal of interest has only been in publication since 1995. Journals typically require several years' time before maturing, when the number and caliber of its publications become typified. Accordingly, it was undesirable to work with the journal's initial years of data.

A paper will be connected to other literature via citations, these other sources can be books, academic journals, proceedings, etc. These other sources cite this work currently, or in the past. The influence of a paper influence can be determined by the links to all the papers that have cited it. In this way, current trends, patterns, and emerging fields of research can be assessed.When using publication data, the location, institute, authors, and date of the publication are of vital importance.

The process of acquiring data will happen via the Institute for Scientific Information (ISI) "Web-of-Science" databank, described in the following section. The subsequent section will concentrate on the parameters of search. Since the downloaded data is fragmented, it must be compiled into a comprehensive database prior to analysis. After the data has been merged, it is ready to be ordered. Only then is it possible to process the data and generate visualizations. The ISI data is downloaded in plain text format, with up to 500 records each time.

4.2 Data processing

The data acquired through ISI web of knowledge has been processed with the software programs provided by Leydesdorff. The results of these programs have been utilized in Microsoft Excel and Access in order to extract the wanted information.

4.2.1 General and geographic development

In order to analyze the volume of knowledge dynamics developed the total activity in the production of knowledge through of publications is identified. This was done by counting the amount of publications, the amount of authors, the amount of institutes and the amount of countries where publications originate from. All this data is primarily accessible from the database files generated by the Cities.exe program provided by Leydesdorff.

The number of publications has been chosen as an indicator. In order to isolate this data on the general characteristics of knowledge development, the different publications were identified. These sets of publications were counted for every year in the timeframe of interest.

The number of actors has been chosen as an indicator. In order to isolate the data on the authors involved in knowledge development, the authors connected with the publications were identified.

This set of data was filtered in order to prevent double entries of single authors. These authors were counted for every year in the timeframe of interest.

In order to analyze what the main contributing regions are to the field of nanotechnology, the addresses of the authors are identified. In order to identify the few regions of great importance all publications where counted per country and city. This allowed for the identification of the countries and cities with the largest knowledge production over the entire span of interest.

The number of countries has been chosen as an indicator**.** In order to isolate the data on the countries producing publications for the knowledge development of nanotech, the addresses for the publications were identified. This set of addresses was simplified to the country of publication. For each country the amount of publications were counted for every year in the timeframe of interest

The number of cities has been chosen as an indicator**.** In order to isolate what countries were main contributors to the knowledge dynamics of the field of nanotech, the different countries producing publications were identified. From this subset of the data, the countries were compiled in a list and the amount of publications were counted and sorted in terms of frequency. From all the years of publications, the top 10 most productive countries were identified. These countries were followed in their development over the entire timeframe of research.

The top cities have been chosen as an indicator**.** In order to isolate what countries were main contributors to the knowledge dynamics of the field of nanotech, the different cities producing publications were identified. From this subset of the data, the cities were compiled in a list and the amount of publications were counted and sorted in terms of frequency. From all the years of publications, the top 10 most productive cities were identified. These cities were followed in their development over the entire timeframe of research.

The top preforming regions have been chosen as an indicator**.** In order to isolate what regions are main contributors to the knowledge dynamics of the field of nanotech, the different cities producing publications were identified. From this subset of the data the amount of publications were counted for all cities and sorted in terms of frequency. For every year of publication the most important cities were identified. These top 10 most productive cities per year were grouped in geographic regions.

4.2.2 Content development

In order to determine whether the field of nanotech knowledge production is diversifying, topics of knowledge production where identified. The amount of publications for these topics where counted and this allows for the mapping of unique or no- unique topics.

In order to determine what the departments in field of nanotech knowledge production are most relevant, the names of the departments associated with the authors have been identified. For these departments the amount of publications has been counted. This allows for the identification of the most important departments active in the field, as well as determining whether these departments are diversifying over the timeframe of interest.

The topics of publications have been chosen as an indicator**.** In order to isolate the data on the topics of publication, the different article topics were identified as provided by the authors. From this subset of the data duplicates were filtered out and the list of topics per year was generated. From this extracted list of topics the amounts were counted.

In order to isolate the data on unique topics of publication, the different article topics were identified as provided by the authors. From this subset of the data, the publications with topics used more than once were extracted and the list of non-unique topics per year was generated. From this extracted list of non-unique topics the amounts were counted and since the total amount was known, one knows the amount of unique topics as well.

In order to isolate what topics are mainly of interest for publication, the different article topics were identified as provided by the authors. From this subset of the data, the publications with topics used more than once were extracted and the list of non-unique topics per year was generated. This extracted list of non-unique topics was sorted in terms of frequency. From all the years of publications, the top 10 most frequently used topics were identified. These topics were followed in their development over the entire timeframe of research.

The top departments have been chosen as an indicator**.** In order to isolate the data on the department involved in publications, the different addresses were identified as provided by the authors. From this subset of the data duplicates were filtered out and the list of departments contributing per year was generated. From this extracted list of departments the amounts were counted.

In order to isolate what departments are most productive in publication, the different departments were identified as provided in the address information of the authors. From this subset of the data, the 10 departments producing most publications over the time of interest were identified. These top 10 departments were followed in their development over the entire timeframe and the amount of their publications counted.

4.2.3 Actor development

In order to identify what combination of active organizations is most predominant the production of scientific knowledge though actor collaboration is identified. This is done by identifying what articles had actors from different organizational backgrounds.

In order to identify the international cooperation in the field of nanotechnology, the production of scientific knowledge though international collaboration is identified. This is done by identifying what articles had authors based in multiple countries.

The cooperation in publication has been chosen as an indicator. The data on the absolute growth of international cooperation is isolated by identifying the articles with two or more authors. From this subset of the data, the articles with more than one country in the address file were extracted. This list of publications was counted and is considered the total number of international publications for every year of publication.

The international cooperation is of interest and data on it was isolated by filtering the articles with two or more authors. From this subset of the data, the articles with more than one country in the address file were extracted. This list of publications was then sorted by number of countries per publication, and for each category, the number of publications was counted.

In order to isolate the data on the relative development of collaboration in the production of article, the articles with two or more authors were identified. This list of publications with multiple authors was counted and is considered the total number of collaborative publications for each year of publication. Since the trend of total publications is clear from the first hypothesis, the relative trend compared to single authored articles is of interest here.

The type of organization has been chosen as an indicator**.** The nature of actors producing publications in the field of nanotech is also of interest. In order to isolate the data on the relative development of collaborating actors of the triple helix model, the addresses of the authors were filtered. This list of publications was filtered for three different types of authors—Institutes, Companies and Universities—for each year of publication (Benner and Sandstorm, 2000). This has been done by keyword filtering, where for each author type, a set of keywords of interest was identified. Since the trend of total publications is clear from the first hypothesis, the relative trend is of interest here.

5. Results

In this chapter the results from the search into the scientific database *Web of Science* for 'Nanotech' from 1997-2011 are presented. The results will be presented in three paragraphs, starting with the general development, in the second paragraph the content development will be presented, and in the final paragraph the actor development will be presented.

5.1 General development

This paragraph presents the general quantitative and geographic field characteristics of knowledge production within nanotech. The first sub paragraph presents the quantitative data on the general aspects of knowledge production for the nanotech sector. The second sub section presents the geographic development.

5.1.1 Publications and authors

Publications are defined in this thesis as the written product of an author on the topic of nanotech. The amount of publications and the associated authors develop over time this is a general indicator of the development of the field of nanotech and shows whether it is growing. The first hypothesis states that the field of nanotech and its associated total activity of knowledge production is increasing. In order to test the hypothesis, data on the general development of the field of nanotech will be presented in this subchapter.

In order to isolate the data on the general characteristics of knowledge development, the different publications were identified. These sets of publications were counted for every year in the timeframe of interest.

The development of publications is shown in figure 1 or Appendix B. The graph shows that the number of annual publications peaked around 2008. After the year 2008 there is a small decrease of about 1-3% annually, which stabilizes around 1150 publications a year from 2008 to 2011.

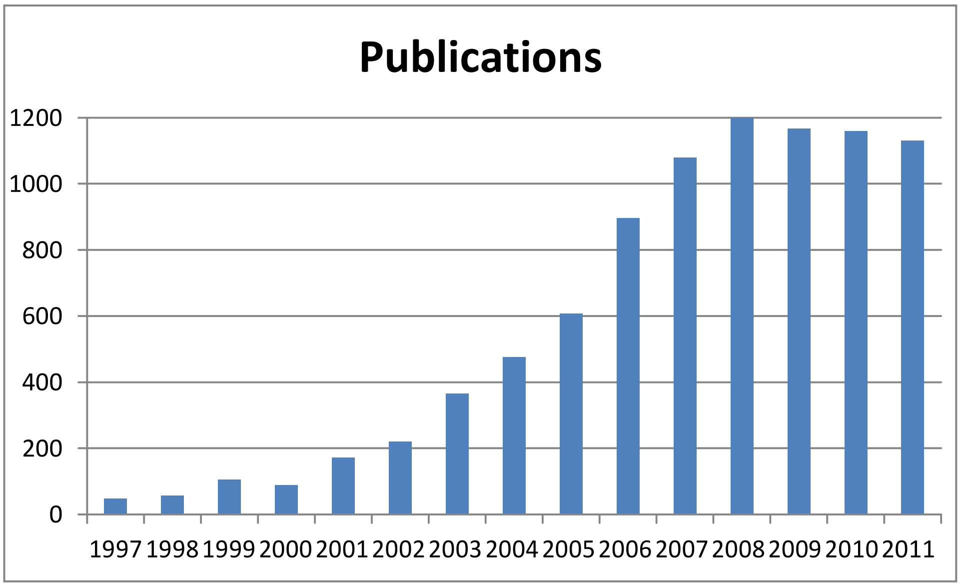

Fig. 1: The total number of publications over the timeframe 1997-2011.

The total amount of publications is one part of the general development of a field. The number of authors involved in producing publications is another general quantitative indicator for the progression of knowledge production in the nanotech field.

In order to isolate the data on the authors involved in knowledge development, the authors connected with the publications were identified. This set of data was filtered in order to prevent double entries of single authors. These authors were counted for every year in the timeframe of interest.

The number of authors producing publications has been analyzed and presented in figure 2 or Appendix C. Similar to the quantity of publications, the number of actors peaked in 2008. After that, the number of authors declined by about 14% over two years in comparison with the publications 1.5 % annually. This is a slightly stronger relative decrease in number of authors than number of publications.

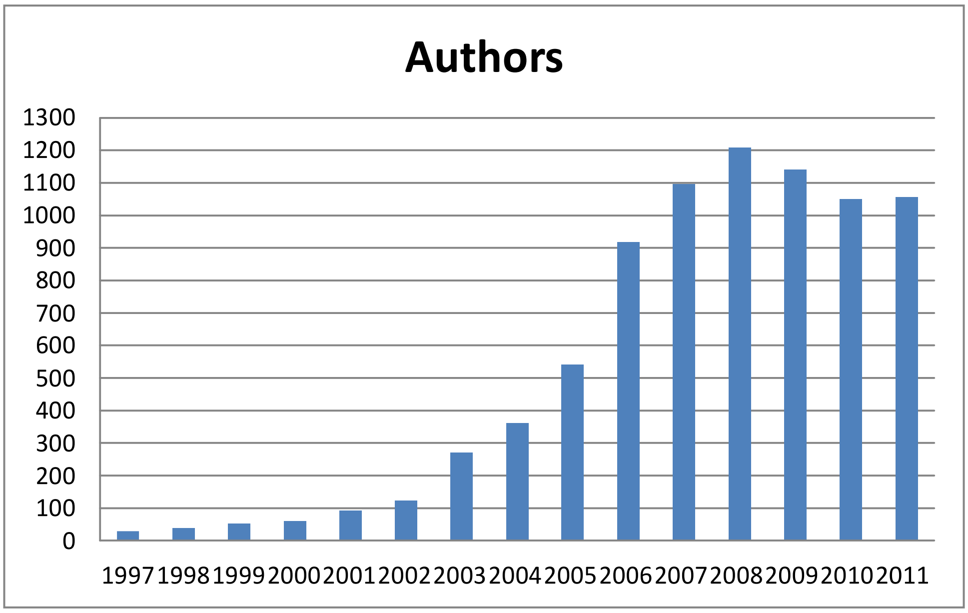

Fig. 2: The total number of authors producing publications per year over the 1997-2011 timeframe.

Both the quantity of publications and the number of authors involved in knowledge production increase up until the year 2008. After 2008, the subsequent years of investigation show a stabilization of output and authors. The first hypothesis states that the total activity in the knowledge production through number of publications is growing. Since the number of publications and authors does not increase after 2008, this hypothesis cannot be validated unconditionally and is therefore rejected.

5.1.2 Geographic development

Nanotech research is a global phenomenon, so the geographical distribution of nanotech was examined. The number of countries producing publications is used as an indicator. The second hypothesis states that knowledge production is spatially separated into a few regions of importance. In order to test this hypothesis, data on the geographic development of the field of nanotech will be evaluated in this subchapter.

In order to isolate the data on the countries producing publications for the knowledge development of nanotech, the addresses for the publications were identified. This set of addresses was simplified to the country of publication. For each country the amount of publications were counted for every year in the timeframe of interest.

The number of countries involved in knowledge production has been growing over time as can be seen in figure 3 or Appendix B. The total number of contributing countries stabilizes around the year 2006. In the most active year of 2008, the number of participating countries was 58, out of 196 total world countries at the time.

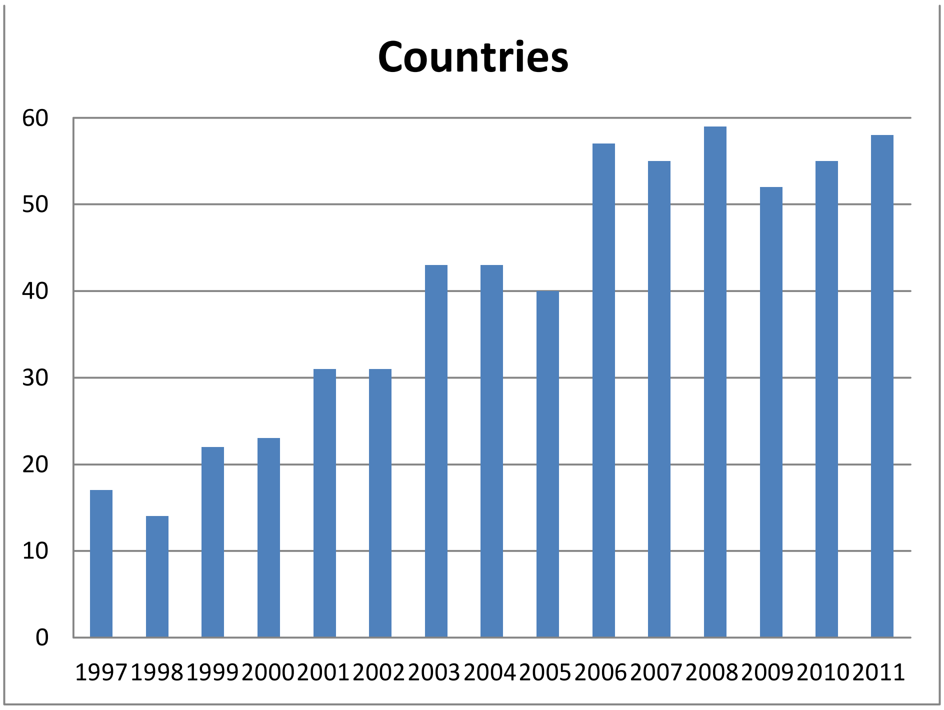

Fig. 3: Number of countries producing publications over the 1997-2011 timeframe.

A country´s activity in producing publications develops over time, some countries remain productive in research while others become less of productive. The most productive countries generally represent strong hubs of research and are the product of long term development.

In order to isolate what countries were main contributors to the knowledge dynamics of the field of nanotech, the different countries producing publications were identified. From this subset of the data, the countries were compiled in a list and the amount of publications were counted and sorted in terms of frequency. From all the years of publications, the top 10 most productive countries were identified. These countries were followed in their development over the entire timeframe of research.

In figure 4 or Appendix D the stability of the top ten countries involved in publication production is presented. It is clear to see that countries like the USA and China are very influential and together nearly produce half of all publications. The top producing countries stabilize their relative portion of knowledge production around the year 2002.

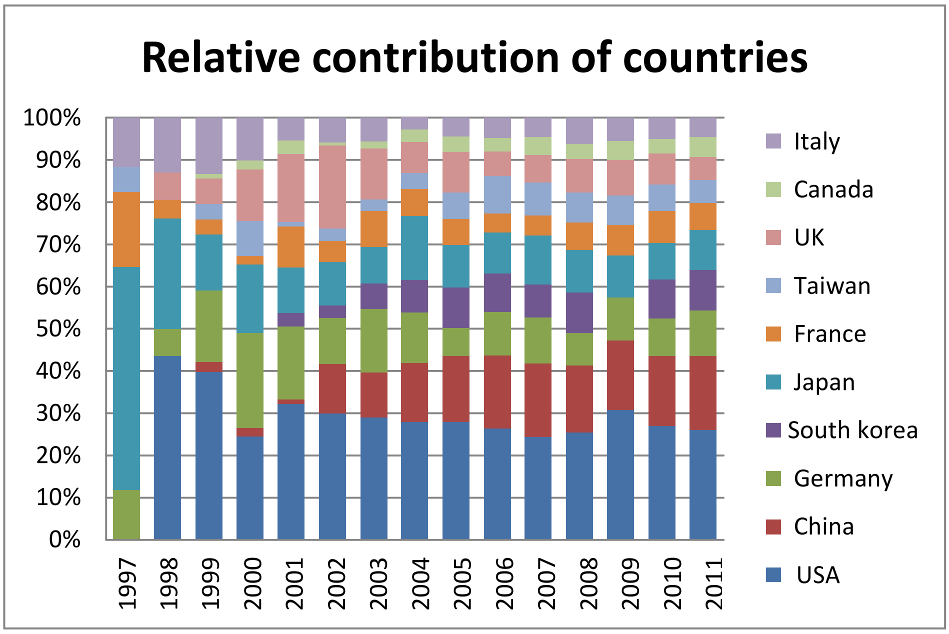

Fig. 4: Top 10 contributing countries producing publications, displayed relative of each other.

A cities activity in producing publications develops over time, some cities remain productive in research while others become less of productive. The most productive cities generally represent strong hubs of research and are the product of long term development. The top ten most productive cities in a knowledge development sense are of interest and are followed over the entire timeframe of interest.

In order to isolate what countries were main contributors to the knowledge dynamics of the field of nanotech, the different cities producing publications were identified. From this subset of the data, the cities were compiled in a list and the amount of publications were counted and sorted in terms of frequency. From all the years of publications, the top 10 most productive cities were identified. These cities were followed in their development over the entire timeframe of research.

The cities producing the largest number of publications over the selected timeframe have been grouped in a top 10 performing cities. Their development over time is shown in figure 5 or Appendix E. The fraction these cities contribute in relation to the global knowledge production peaks in the year 2006 at 70 %. After the year 2006, the peak declines. In 2011, the top ten cities produce only about 50% of all global publications.

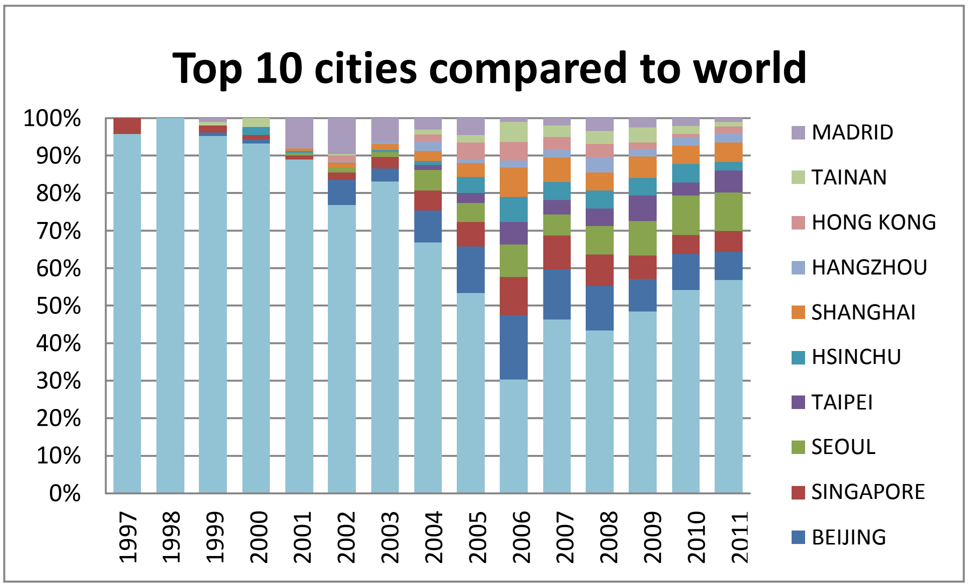

Fig. 5: Top 10 contributing cities producing publications, displayed relative of each other.

From the annual data presented on the top performing cities it is clear that a large portion of the body of knowledge in the field of nanotech is produced in a small group of locations. It is unclear how these locations relate to each other in a geographic sense. Therefore the development over time of geographic regions has been investigated.

In order to isolate what regions are main contributors to the knowledge dynamics of the field of nanotech, the different cities producing publications were identified. From this subset of the data the amount of publications were counted for all cities and sorted in terms of frequency. For every year of publication the most important cities were identified. These top 10 most productive cities per year were grouped in geographic regions.

The top preforming cities of every year are grouped by regions and presented in figure 6 or Appendix F. The most important regions have been found to be Europe, USA, Asia and Russia. From this figure it is apparent that since 2004, 9 cities have been located in Asia. Earlier in this timeframe, other continents played a larger role in publication production. However, the lead was gradually taken over by Asian cities.

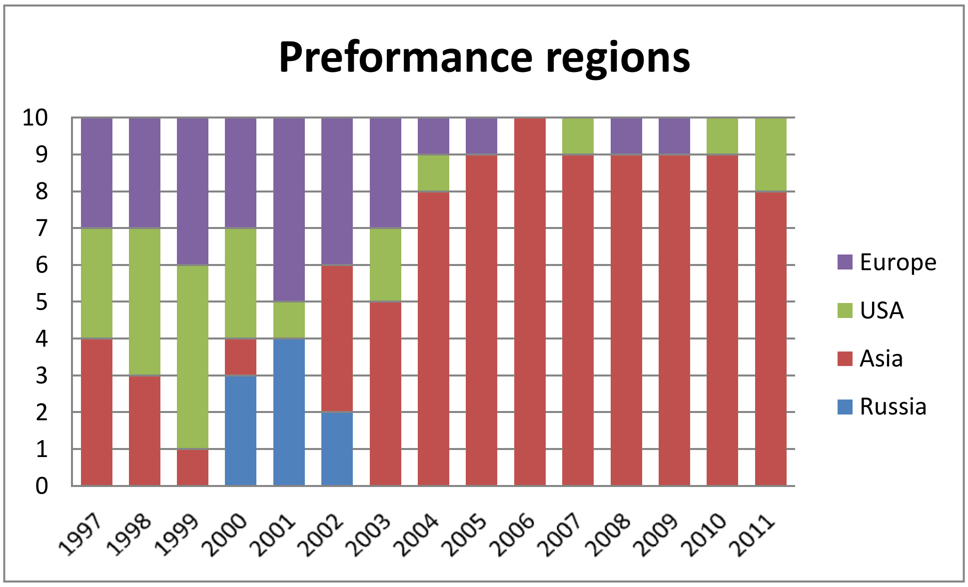

Fig. 6: Top preforming regions.

The top producing cities are located in or near China, as can be seen in figure 7. This implies strong clustering of knowledge production in this region. The only top performing city outside of Asia is Madrid, which has had a history of nanotech knowledge since the very beginning of the timeframe.

Fig. 7: Number of top preforming cities per continent.

The stabilization of the total number of countries involved, as well as a stable contribution from specific countries, indicates that the body of knowledge of nanotech is concentrated within a few geographical regions. By focusing on the top 10 performing cities and the top performing continents, it is shown that that knowledge production is dispersed amongst a few, distinct countries and cities of importance, primarily China and its neighbors such as South Korea, Taiwan and Malaysia. The second hypothesis stating that knowledge production is spatially separated in a few regions of importance can be validated and is therefore accepted.

5.2 Content development

The characteristics for the nanotech network in relation to its content are determined by analyzing the development of knowledge production. This can be achieved by looking into the development of topics in the field of nanotech or into the development of departments. In order to achieve this, the topic development is presented in the first sub paragraph and the department development in the second sub paragraph.

5.2.1 Topics of publication

The topics of publication are defined in this thesis as the topic chosen by the author as to what the publication addresses. These topics develop over time; some topics will fade away, whereas some will become important and dominate the field. The associated third hypothesis states that the topics in knowledge production are developing in an increasingly divergent manner. In order to test the hypothesis, data on the topic development of the field of nanotech will be presented in this subchapter.

In order to isolate the data on the topics of publication, the different article topics were identified as provided by the authors. From this subset of the data duplicates were filtered out and the list of topics per year was generated. From this extracted list of topics the amounts were counted.

The number of published topics produced by actors in the network of nanotechnologies is presented in figure 8 or Appendix G. This graph shows the quantity of identifiable topics in the field of nanotech for each year. These topics can be differentiated on the basis of topics submitted by authors as part of their publication. Similar to the total number of publications, the number of topics peaks in 2008.

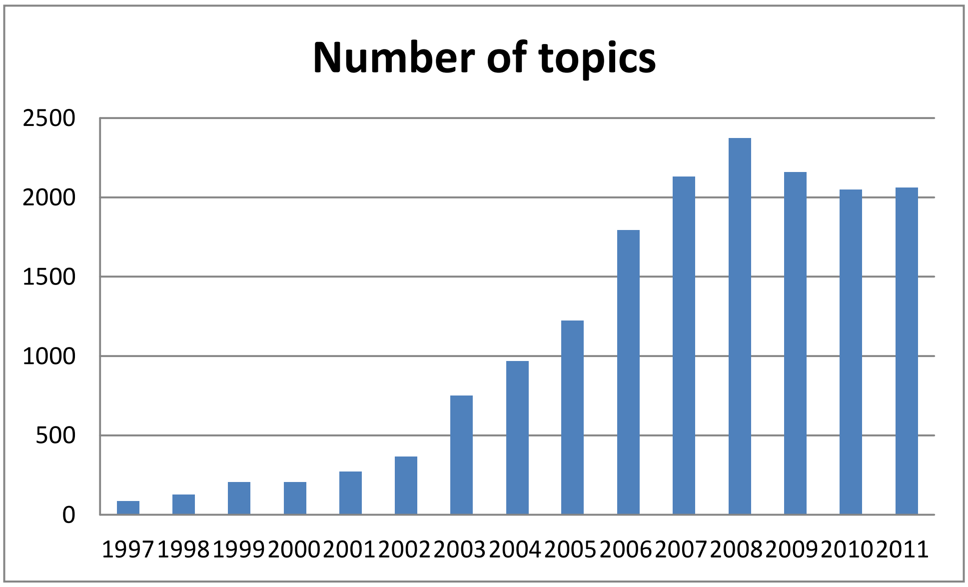

Fig. 8: Number of topics in the produced publications.

Unique topics of publication are defined in this thesis as the topics chosen by the author as to what the publication addresses that have not been used in that year. Topics develop over time and an increase in the relative amount unique topics in a field indicates the field is developing field and diversifying.

In order to isolate the data on unique topics of publication, the different article topics were identified as provided by the authors. From this subset of the data, the publications with topics used more than once were extracted and the list of non-unique topics per year was generated. From this extracted list of non-unique topics the amounts were counted and since the total amount was known, one knows the amount of unique topics as well.

Topics addressed in multiple publications versus topics used in one publication are presented in figure 9 or Appendix G. Unique topics are only used in one publication that year, compared to topics used in multiple publications. After the first three stable years of around 15% unique topics, a gradual increase of unique topics sets in from 2000 on. This trend stabilized around the year 2006 at 30% unique topics every year. This data indicates an increase of divergence in nanotech topics over the period 2000-2006.

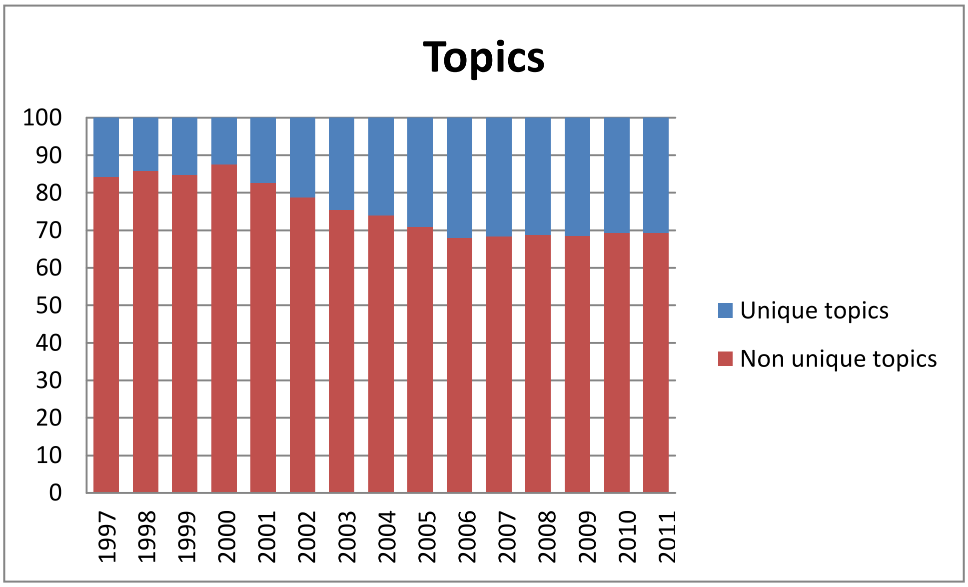

Fig. 9: Distribution of unique topics compared to non-unique topics

When topics are chosen for research by multiple authors, this shows that there is a relatively stronger interest in a direction of research. As topics develop over time some remain popular directions of research while others become less of interest. The most popular topics generally represent strong traditions of research and are the product of long term development.

In order to isolate what topics are mainly of interest for publication, the different article topics were identified as provided by the authors. From this subset of the data, the publications with topics used more than once were extracted and the list of non-unique topics per year was generated. This extracted list of non-unique topics was sorted in terms of frequency. From all the years of publications, the top 10 most frequently used topics were identified. These topics were followed in their development over the entire timeframe of research.

The most popularly used topics addressed in multiple publications are presented in figure 10 or Appendix H. After the first four years all the topics have been introduced into the field. It takes until 2004 until the topics stabilize their relative faction in the top ten most popular topics, after this year the field has become very stable.

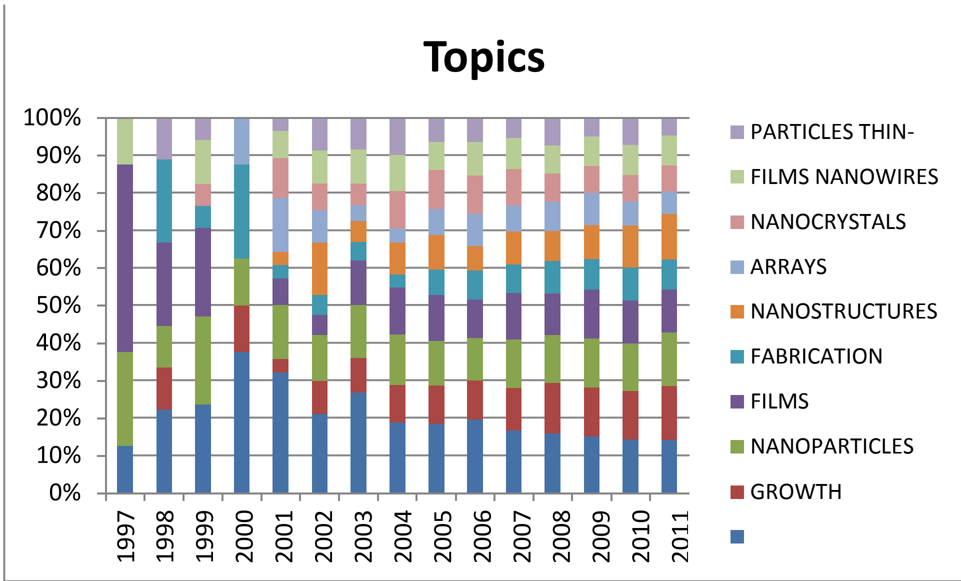

Fig. 10: Top 10 most popular topics

Similar to the total number of publications, the number of topics peak in the year 2008. Around the year 2006 the unique topics stabilize at 30% every year. The top ten most popular stabilize after the year 2004. This data indicates an increase of divergence in nanotech topics until the period 2006-2008. After this the topics themselves do not continue to diverge, therefore the third hypothesis cannot be validated unconditionally and is rejected. The topics of knowledge production in the field of nanotechnology are not increasingly divergent

5.2.2 Departments

A field of new science is developing to be increasingly multi-disciplinary when there is emergence of new departments within the field The fourth hypothesis states that resources used in the field of nanotech increasingly diversify. To test this hypothesis, data on the departmental development of the field of nanotech will be presented in this subchapter.

In order to isolate the data on the department involved in publications, the different addresses were identified as provided by the authors. From this subset of the data duplicates were filtered out and the list of departments contributing per year was generated. From this extracted list of departments the amounts were counted.

The number of department producing articles in the field of nanotechnologies is presented in figure 11 or Appendix I. This graph shows the quantity of identifiable departments in the field of nanotech for each year. Similar to the total number of publications, the number of topics peaks in 2008, however it is remarkable to see that in 2011 the amount of departments seems to grow again.

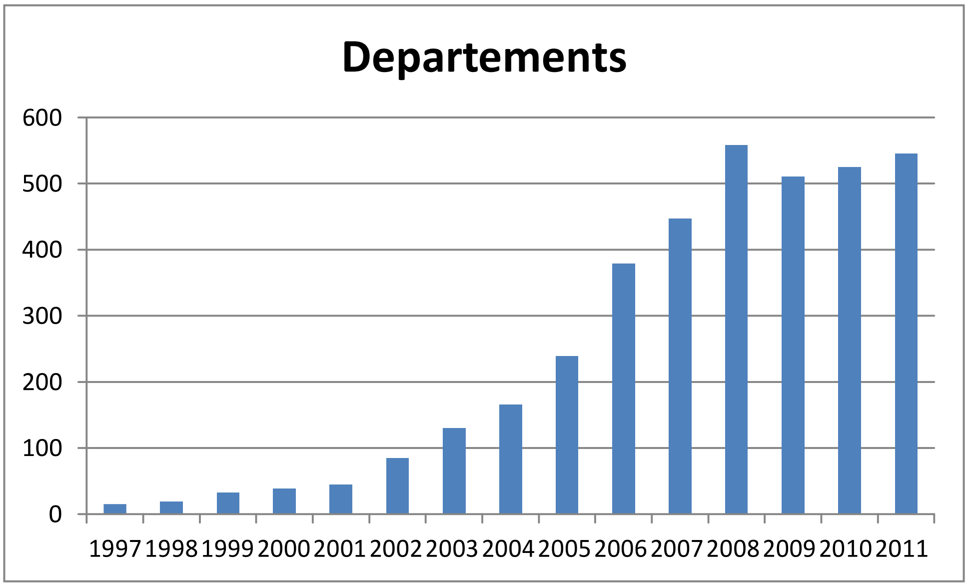

Fig. 11: Top 10 most popular topics

Besides the absolute growth of departments, it is of interest to see what departments are most popular. New departments are set up for research in a specific field this shows that there is a relatively stronger interest in a direction of research. As departments develop over time they will lead to the setup of new departments in popular directions of research while others become less of interest. The most popular departments generally represent strong traditions of research and are the product of long term development.

In order to isolate what departments are most productive in publication, the different departments were identified as provided in the address information of the authors. From this subset of the data, the 10 departments producing most publications over the time of interest were identified. These top 10 departments were followed in their development over the entire timeframe and the amount of their publications counted.

In order to determine whether the nanotech field is multi-disciplinary, the emergence of new departments within the field is presented in figure 12 or Appendix I. on a relative scale. The nanotech field incorporates increasing numbers of different sub-disciplines, diverging and acquiring knowledge externally. Since nanotech is a sub branch of physics, the department of physics is the largest contributing sub-discipline, shown by the blue at the bottom of the graph. From the year 2002 onwards, there is strong differentiation and different sub-fields gain influence within the nanotech field.

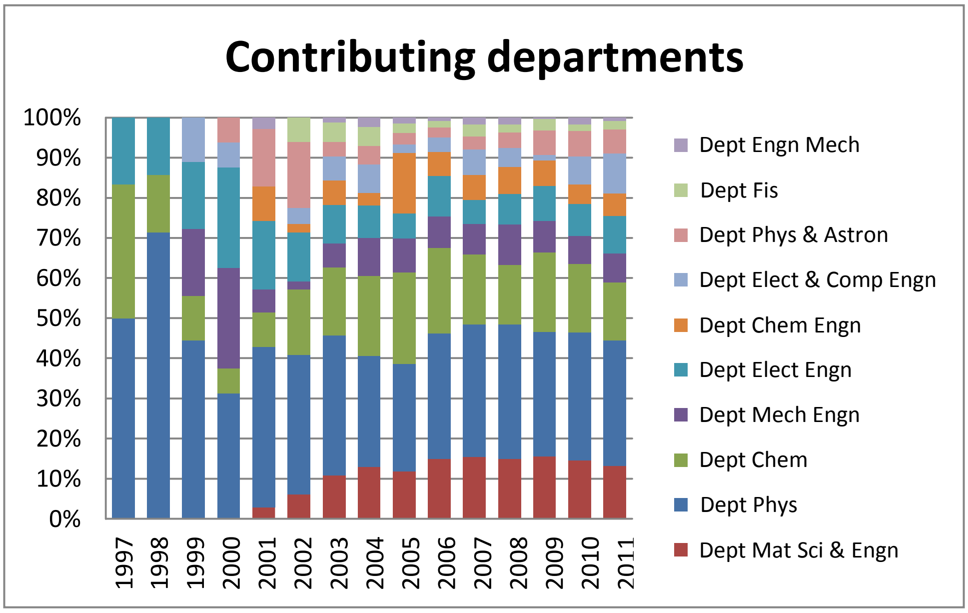

Fig. 12: distribution of departments

From graph 11 it can be found that the total number of department peaks in 2008 and stabilized. When comparing this to the total number of publications, the number of departments is relatively growing after 2008.From graph 12 it can be found that the distribution of departments has been diversifying over the timeframe. From the data on diversifying departments it is concluded that the fourth hypothesis can be validated. The use of resources in the field of nanotech is diversifying increasingly.

5.3 Actor development

The characteristics of knowledge production within the nanotech network in relation to the development of actors from the triple helix model are presented in this paragraph. The development of international cooperation between actors is presented in the first sub paragraph. In the second sub paragraph, the co-authorship results are presented. Finally, in the last paragraph the distribution of actors in publications is presented.

5.3.1 International cooperation

International cooperation is defined in this thesis as a publication with multiple authors originating from two or more different countries. The intensity of this activity amongst authors is regarded as an indicator for intensity of international cooperation. The associated fifth hypothesis states that the nanotech network is increasingly producing scientific knowledge though international collaboration. This hypothesis has been evaluated through the two aspects of absolute and relative growth of international cooperation. In order to test the hypothesis, data on the development of international cooperation in the field of nanotech will be presented in this subchapter.

The data on the absolute growth of international cooperation is isolated by identifying the articles with two or more authors. From this subset of the data, the articles with more than one country in the address file were extracted. This list of publications was counted and is considered the total number of international publications for every year of publication.

The number of international publications produced in the network of nanotechnologies is presented in figure 13 or Appendix J. This graph shows publications with multiple authors originating from 2 or more countries. In the chart it can be seen that similar to the total number of publications, the number of international publications peak in 2008, after which the number of international collaborations decreases and stabilizes.

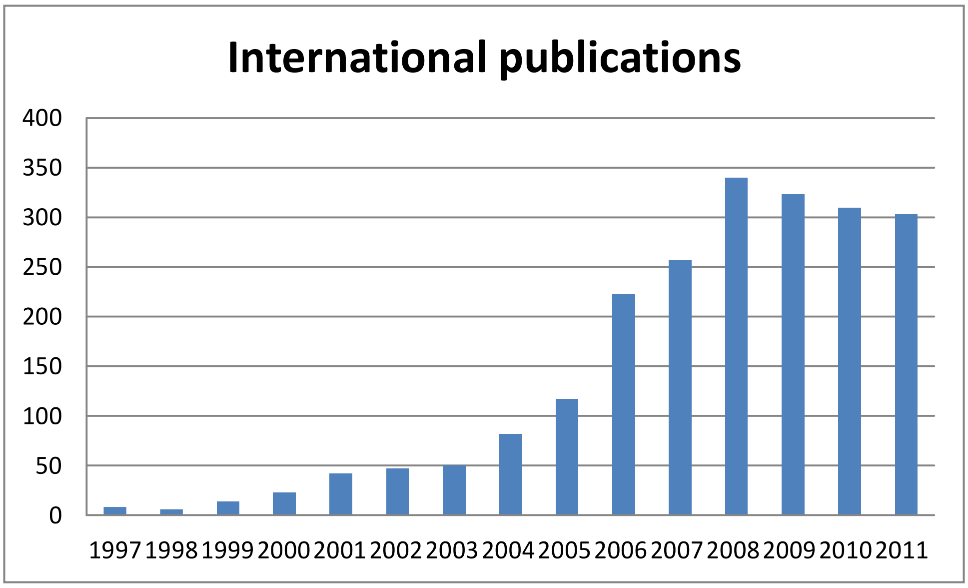

Fig 13: Number of international publications

Figure 13 shows the total number of international cooperation in publications. Note that this measure does not differentiate between the number of countries per publication. In order to determine how the number of countries per publication developed, further investigation was conducted. This is referred to as the "relative development", it focuses on determining how the relative number of publications has developed over the timeframe of interest.

Similar to figure 13, the international cooperation data was isolated by filtering the articles with two or more authors. From this subset of the data, the articles with more than one country in the address file were extracted. This list of publications was then sorted by number of countries per publication, and for each category, the number of publications was counted. This is considered the relative distribution of number of countries associated with each publication and is presented in figure 14.

From figure 14 or Appendix J it can be seen that the relative share of publications involving only one country has represented the largest share of publications over the timeframe of interest. The share of publications with multiple countries in international cooperating fluctuates until the year 2006, when it stabilizes with around 25% of all publications are generated by international cooperation. What is noticeable is that about 20% of publications have 2 countries or more active in the publication.

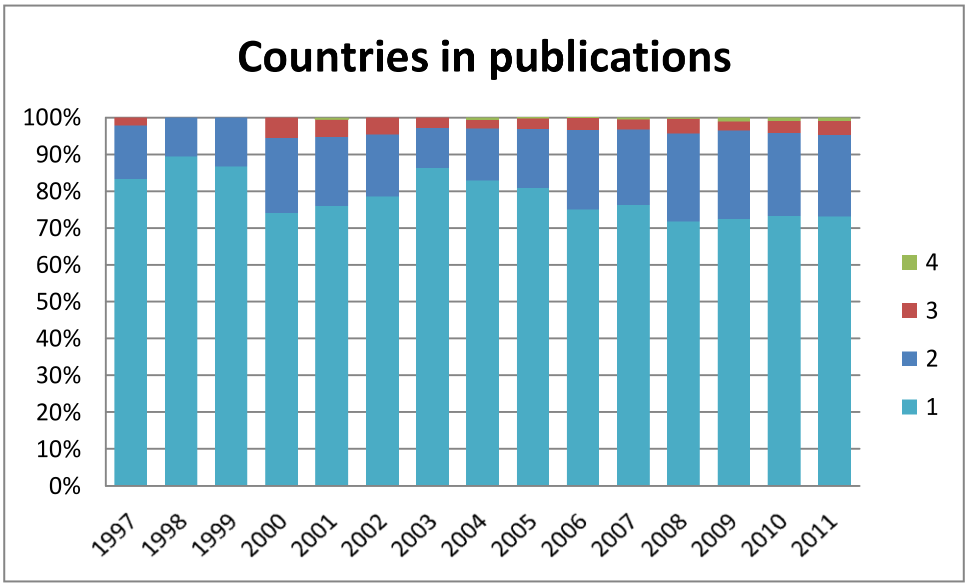

Fig 14: Relative distribution of countries per publication

The analysis of international cooperation was based on an absolute development of the amount of international publications combined with a relative analysis of the direction of development. In absolute terms, the number of international publications shows a similar trend as the total number of publications. Therefore, the number of international publications grows up until the year 2008, after which the trend stabilizes. The relative distribution of number of countries for every publication also stabilizes around the same year.

Through the two aspects of absolute and relative growth of international cooperation, the hypothesis has been tested. An absolute and relative stagnation of the trend towards international cooperation had been found. Because of these two aspects, the fifth hypothesis cannot be validated and is therefore rejected. Concluding from this the nanotech network is not increasingly producing scientific knowledge though international collaboration.

5.3.2 Collaboration & contributors

Collaboration in this thesis is defined as a publication with multiple authors. The nature of contributors in the field of nanotechnology can be of different actor type when using the triple helix model. The associated hypothesis states that the nanotech network displays increasing collaboration and different types of knowledge producing actors. This hypothesis has been evaluated through two aspects: relative growth and the kind of actors contributing to the field. In order to test the hypothesis, data on the development of actors from the triple helix model in the field of nanotech will be presented in this subchapter.

In order to isolate the data on the relative development of collaboration in the production of article, the articles with two or more authors were identified. This list of publications with multiple authors was counted and is considered the total number of collaborative publications for each year of publication. Since the trend of total publications is clear from the first hypothesis, the relative trend compared to single authored articles is of interest here.

The relative share of multiple authored articles compared to single authored articles is presented in figure 15 or Appendix C. From this figure it is clear that the relative distribution of authors per article is very consistent. Over the entire timeframe about 20% of the articles have been co-authored. From this it can be concluded that for this data co-authorship is related to absolute publication output

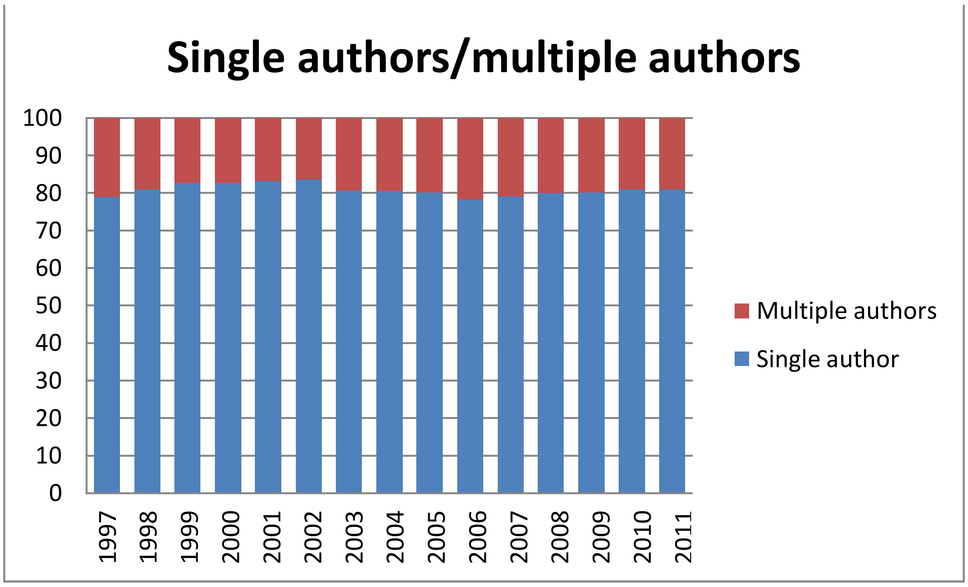

Fig 15: Relative distribution co-authors compared to single authors

The nature of actors producing publications in the field of nanotech is also of interest. In order to isolate the data on the relative development of collaborating actors of the triple helix model, the addresses of the authors were filtered. This list of publications was filtered for three different types of authors—Institutes, Companies and Universities—for each year of publication. This has been done by keyword filtering, where for each author type, a set of keywords of interest was identified. Since the trend of total publications is clear from the first hypothesis, the relative trend is of interest here.

The relative distribution of different groups of actors in nanotech is presented in figure 16 or Appendix K. Initially, institutes and companies had predominant influence in the field. After 2002, this role was over taken by universities, which constituted approximately 75% of the groups of cooperative actors. Since 2002, the relative distribution of actor type has been fairly consistent.

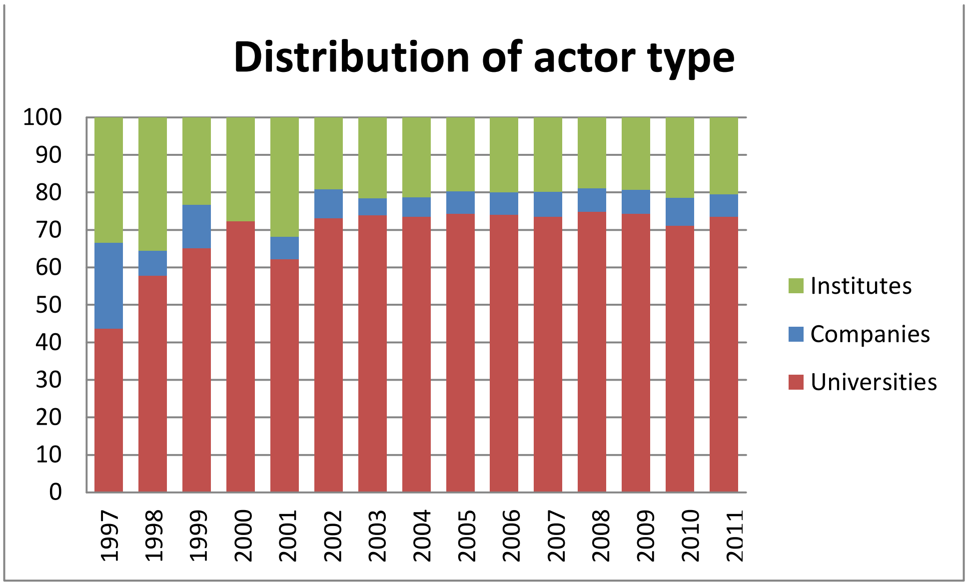

Fig 16: Relative distribution of actors

The distribution of coauthors and the distribution of actors in the field of nanotechnologies are consistent. The sixth hypothesis, stating that the nanotech network displays increasing collaboration between different types of knowledge producing actors, can therefore not be validated.

6. Conclusion

In this chapter the results of this research will be coupled with the questions of research that were raised. The answers to the questions of research and the associated conclusions will be presented. First the three sub questions of research will be addressed finally the main question of research will be addressed.

6.1 General development

The first part of the first sub question of research addresses how the volume of knowledge dynamics has developed over time. From the data presented on the general development of the field of nanotech it can be found that the volume of knowledge production increased substantially until the year 2008. After the year 2008 the field stabilized in terms of output, the effect was noticeable of stabilization can be seen in the total amount of publications per year and in the total amount of authors per year. This is in conflict with the expectations raised from the statements of Bonaccorsi who states that the development of new scientific areas will create growth of knowledge production that is exponential for the scientific field (2008). The data found in this thesis is not what was expected of a rapidly developing field like nanotech. The first hypothesis could therefore not be validated unconditionally and was rejected. From this data it was concluded that the activity in the production of knowledge through of publications is not growing.

The second part of the first sub question of research addresses what are the main contributing regions in the field over time are. From the analysis of the geographic development of the field of nanotech it was found that there are a few main contributing regions. The amount of countries participating in the research into nanotech was growing until the year 2006 when it stabilized around 55 participants. Initially the field developed with a strong basis of researchers in Europe and the US. After a few year there was a flare of activity in Russia. But since 2002, the dominant region has been East Asia, including China, South Korea, Taiwan and Singapore, this effect was noticeable in cities and countries This is in line with the aspect of knowledge development that geographical proximity to crucial knowledge is important (Sorenson et al. 2006). The second hypothesis was tested and therefore validated. From this data it was concluded that he the knowledge production in the field of nanotech is spatially separated in a few regions of importance.

In answering the first sub question of research, the general development of the field of nanotech has been questioned. Trough investigating the general characteristics of the field it was found that the volume of knowledge dynamics grew strong for the initial period of the field, until it stabilized in the year 2006. This effect of stabilization can be seen in the publications and in the amount of authors, this was an unexpected result. For the geographic development the data on the field of nanotech displayed the expected behavior where south East Asia dominated the field in terms of production of publications from the year 2006 with 50% to 70% of all publications.

6.2 Content development

The first part of the second sub question of research addresses how the topics of nanotech knowledge production diversify over time. From the data presented on the content development of the field of nanotech it can be found that the volume of topics increased substantially until the year 2008. After this year the amount of topics decreased slightly and then stabilized. The pattern shown in the data is very similar to the development of total publication production. The nature of the topics of knowledge production increasingly diversified from the year 2000 to 2006. More unique topics were introduced every year, until the fraction of unique topics stabilized. This diversification of topics suits well with the expectation of Bonaccorsi that new sciences grow more diverse. This is due to unifying theories that lead to an explosion or proliferation of several competing sub-theories (2008). When looking at the development of top ten topics of research, it is clear that up until the year 2002 the fractions of topics were not stabilized. This initial period can be seen as divergent progression involving the creation of new subfields and is common in new science (Collins et al., 2003). After 2002 the relative importance of topics was very stable and the field was not divergent when looking into topics. The third hypothesis could not be validated unconditionally and was therefore rejected. The topics of knowledge production in the field of nanotech are not increasingly divergent, since their divergent behavior ended after the period 2002-2006.

The second part of the second sub question of research addresses what departments are most relevant over time. From the data presented on the content development of the field of nanotech it can be found that the volume of departments increased substantially until the year 2008. After the year 2008 there was a dip just like in all the other data, however there was a relatively larger growth after the dip, leading to number of publications in 2011 that was nearly the 2008 number. Over the entire timeframe the departments active in the field increasingly diversified, with new departments entering the field and more established departments gradually losing relative importance. This suits the expectation that new sciences are increasingly multi- and interdisciplinary (Gibbons et al., 1994. Where a rapid progress is expected for the field of new sciences and will continue to “create new fields of research at high pace even in their maturity” (Collins et al, 2003, Luscombe, 2001). The most relevant department is physics, which is in line with the fact that nanotech is a subfield of physics. Also the department of Chemistry, Electrical engineering and Computer science are very productive. Continuing, the fourth hypothesis was tested and validated. From the data it was found that the field increasingly utilizes diverse resources through different departments.

In answering the second sub question of research, the content development of the field of nanotech has been questioned. Trough investigating the content characteristics of the field it was found that the volume of topics and department dynamics grew strong for the initial period of the field, until it had a decline after the year 2008. Besides the absolute development, indications have been found for diversification of the topics up until the year 2006. Also the departments increasingly diversified over the timeframe. From this it can be concluded that the nature of knowledge production within the field of nanotech has diversified strongly over the initial part of the field’s development. After this the diversification slowed down. For the development of knowledge the department of physics is most dominant in the field.

6.3 Actor development

The first part of the third sub question of research addresses how international cooperation developed over time. From the data presented on the actor development of the field of nanotech it can be found that the volume of international cooperation increased substantially until the year 2008. After the peak in 2008 there was a slight decline as was seen in most of the data and for the following years knowledge production was generated with a stable amount of international cooperation. The amount of countries per publication in international cooperation gradually increased as well until the year 2000. This is in line with the expectation that actors in a search regime require cooperation with other actors in order to share their diverse abilities, creating new ideas (Bonaccorsi, 2007). Due to the stabilization of the field the fifth hypothesis could not be validated. This is because the field of nanotech is not increasingly producing scientific knowledge though international collaboration. This was only true for the initial phase of development.

The second part of the third sub question of research addresses what active organizations are most predominant over time. From the data presented on the development of cooperation the field of nanotech it can be found that the share of co publications is very stable over the entire timeframe of interest. This is what was expected by Bonaccorsi who stated that:" New sciences make use of new forms of complementarity due to required heterogeneous competences and interaction with actors localized at different institutional levels (2008)." The different actors from the triple helix model active in the field stabilized with a strong focus of 75% on universities for knowledge production. The institutions and companies represent about 25% of all publications for the period 2002 to 2011. This is in line with the expectation that frequent interaction between universities and institutes is necessary to aid the development of the scientific discipline (Luscombe, 2001). This complementary relationship can be beneficial for institutions allowing them to seize opportunities provided by new industries and enable the revival of mature industries, (Martin, 2010) Continuing, the sixth hypothesis was tested and could not be validated. The nanotech field does not display increasing collaboration between different types of knowledge producing actors.

The last characterization of the field of nanotech addresses the source of knowledge production in this field. Here it is found that international cooperation is an important aspect of the field. However it is not a continually growing aspect since it has stabilized. There is a very stable distribution of the amount of countries per publication, with the 80% of publications with 1 or two countries per publication. The main contributing actors of the triple helix model in the field of nanotech are universities, the distribution of actor type stabilized with 75% of all publications originating from this actor type.

6.4 Main question of research

The main question of research addresses what the characteristics of the nanotech search regime in the 1996 to 2011 period are. From the three sub questions addressing this main question it was found that the field of nanotech has been growing in an expected rate for a new science, but since the year 2006 the field has stabilized. This stabilization occurred in nearly all absolute indicators that were used in this analysis. The field has been highly concentrated over the timeframe of interest, the geographical location of the field changed over time, but in 2011 the last year of interest the field is concentrated in East Asia. The volume of topics grew strong in the field of nanotech, also the departments increasingly diversified over the timeframe. The nature of knowledge production within the field of nanotech has diversified strongly over the initial part of the development. After this the diversification slowed down. For the development of knowledge the department of physics is most dominant in the field. International cooperation is an important aspect of the field, it is not a continually growing aspect also the amount of countries per publication has stabilized. The main contributing actors of the triple helix model in the field of nanotech are universities.

This analysis is intended to supply interested parties in the field of nanotech with insight into potential opportunities in the field. From the data It is clear that the diversification of the field has slowed down considerably. This shows the field has entered into a more mature state, with a geographic strong presence in the East Asian countries. In respect for western nations such as Europe this is highly unpleasant as these fields are expected to dominate the scientific Landscape of The 21st century (Bonnacorsi 2007). This in contrast with the intentions set by the European Union concerning the importance of this field. In the opinion of this writer it will require a very strong drive of governments to obtain the originally important position of western nations in the field. This can be very costly and therefore shows an interesting parallel with the quantum tunneling experiments, where a particle will be able to tunnel through any material with enough energy and positioning that it classically could not pass through, this is visually portrayed on the front page. The effect of tunneling is often explained using the Heisenberg uncertainty principle and the wave–particle duality of matter described by the Schrodinger equation shown on the first page. Quantum tunneling falls under the domain of quantum mechanics: the study of what happens at the quantum scale and the foundation of nanotech. Likewise as with quantum tunneling, western countries will need to concentrate large amounts of energy and focus in order to maintain any kind of position in this field over longer periods of time. But as the title of the thesis has already portrayed: “Infinite energy will tunnel through everything.”

For policy makers it is vital that the systemic innovation capabilities of this subfield will need to be improved, an important aspect lies in interactive learning. Therefore policy instruments need to be aimed at promoting innovation networks among firms and encouraging local university–industry partnerships (Todtling, 2002). This will be a way in which specific branches of nanotech can be stimulated locally. Besides building these relationships it will be vital for knowledge generation and diffusion that policy aims at improving the institutional infrastructure. This can be achieved by creating local research centers, these should have access to with high level, specialized expertise (Tödtling&Tripp, 2005). For a governmentally stimulated approach to the further development of the field of nanotech, it is this authors opinion that a highly specialized approach is required as described in Smart specialization. In that respect the most popular topics of research and the newly generated departments are of interest, as they give a qualitative overview of established parts of the nanotech field. In order to detect a specific sub branch of nanotech that is rapidly developing and potentially fruitful there are many options to be detected from this data. Research programs can be successful in some regions while fail to achieve expectations in other situations, this is based on the path-dependent dynamics scientific knowledge production (heimeriks and leydesdorf 2012) The exact choice would depend on the specific country and associated system and would therefore require specific research for that unique situation.

7. Discussion

In this chapter a few aspects at the basis of this thesis will be discussed. This involves some of the choices made and the consequences of them, it will continue with the advice on what could be done differently in a subsequent research.

7.1 Quantitative verses qualitative

In this thesis journal publications were chosen as an indicator for determining the characteristics of field of nanotech. However the method used did not take into account what the impact factor of the publication was. Bonnacorsi states that “European science is strong in fields characterized by slow growth and weak in those characterized by rapid or turbulent growth”. This is a result found from the data in this research making view point in this situation interesting. The case has been made by Bonnacorsi that the quality of papers is a very important measure, as he states that “European science is only quantitatively comparable to US science but is weaker in the overall quality and is severely under-represented in the upper tail of scientific quality”. This view point makes it interesting to incorporate an analysis on the quality to see how the results would compare. Another point made by Bonnacorsi is “European science is strong in fields characterized by a convergent pattern of growth and weak in those characterized by a divergent or proliferating pattern of growth”. This is of importance since the most value is added through divergent patterns of growth (2007). It can be argued that this research has been based on average values, however for successful science policy it would be more useful to focus on the upper percentile portions of the distribution of science for the purpose of policy-making (Bonnacorsi 2007).

7.2 Historical aspects

The thesis does not focus on the scientific historical developments of countries before the emergence of the science of study. It is possible that countries already have a well-established field that is closely related with top scientists. The advantage of a large knowledge base can be an advantageous position and can lead to misleading growth rates. As for instance found by Lynne who stated that “the size of the cumulative knowledge stock of articles published in non-nano tech fields in a given geographical region has a significant positive effect on the rate of production of nano tech articles and patents in that region.”(2007)

7.3 Journals

The thesis uses one journal for the analysis, as journals are more up to date and consist of a larger database than books (Leydesdorff, 1987). The research field of nanotechnologies is for a great part represented by one journal: ‘Nanotechnology’ which is the largest journal. In order to make sure that this is valid representation, the data of ‘Nanotechnology’ can be compared with a larger data set which contained most of the publications in the field. Further research could for instance make use of the open-access digital library called “NanoBank”. This database has compiled articles and patents in the field of nanotech from various sources all related to nanotech (Lynne, 2007).

7.4 Data type

The thesis does not take into the aspects of the nanotech search regime does not distinguish between 'independent' or 'dependent' variables. The relationships among variables can be influential on the results. The analysis focused solely on the dynamics of the search regime and its network.

The data used in this analysis is scientific output; this can cause a skewed result with a focus on institutes and universities where the role of industrial actors is less dominant. This research focuses on a science-based field and its knowledge dynamics, therefore it is logical that most information retrieved concerns mainly scientific actors instead of industrial actors.

The involvement of industrial actors was captured through the use of the triple helix model is assumed that for a more commercialized industry, the relevance of industrial actors would be higher. This is because the more important the socio-economic application context would be, the more industrial institutes would be involved in the knowledge production (Bonaccorsi, 2007).

The search regime approach is based on analysis on the level of the scientist. This could limit the approach in identifying other possibly important factors such as industrial actors or commercial actors. This is partly also dependent on the limitations of the data source used to conduct the analysis.

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Appendix A Acquiring data

As stated the publication data required for the study has been obtained from the Web-of-Science database, this is provided by the publisher Thomson Reuters. This online academic citation index allows one to access multiple databases for research and in-depth exploration of different scientific and academic. The Reuters Web of Science has indexing coverage from the year 1900 to the present. Using an IP address at the University of Utrecht, one can gain access to the *Science Citation Index.* The database can be found in the digital library of the university or by directly accessed.

Select the "Web of Science" as product, use "advanced search" and refine your search so that you have more control over the selection. Now in order to execute a search one needs to type a term at the search field and delimit its field of search, after composing the search, click on OK and continue.

Now the results will be generated and one can browse through these papers. The database provides various options for sorting and analysing the results. For this research it is important to sort the data on their publication year. Therefore one needs to focus on a specific year and save these results. In order to save these results one needs to navigate to the bottom right side of the screen. There one can find the option "Output Records". With a maximum of 500 at a time these results will be saved for further processing, all international publications are used.

Via the Web of Science database the data was searched via the above stated method, this resulted in the generation of 9365 hits. The time delimitation has been chosen since the chosen journal has only been in operation since 1995. Since any journal has an initial phase where the amount of publications need to mature and it is undesirable to work with a journals data from the initial years. The following parameters of search were used:

- The search term was "Nanotechnology" and it was limited to publication only.
- The data was time limited with 15 years, starting from January 1997 until December 2011.
- The countries of publication are all nations within the European Union zone.
- The data is sorted by publication year and was downloaded 500 at a time.

When downloading the data, the full records were acquired, plus the abstract and the cited reference. This data is saved to a plain text file and is stored in a different folder for each year of publication.

Appendix B Publications per Country

Year	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Algeria	0	0	0	0	0	0	0	0	0	2	0	1	0	2	1
Argentina	0	0	0	0	0	0	2	1	4	5	6	3	2	3	1
Armenia	0	0	0	0	1	0	0	0	0	0	2	1	0	0	0
Australia	0	0	0	2	0	4	6	4	9	19	17	28	20	21	24
Austria	0	0	1	1	0	0	2	1	2	1	6	6	4	5	10
Azerbaijan	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Belgium	0	1	0	3	4	7	3	5	5	5	12	14	9	15	5
Brazil	0	0	2	0	1	2	4	6	8	14	17	15	19	26	23
Bulgaria	0	0	0	0	0	2	1	1	0	1	1	0	1	0	1
Byelarus	0	0	0	0	0	0	0	0	0	3	1	2	3	3	1
Canada	0	0	1	1	3	1	4	10	16	21	33	30	34	29	38
Chile	0	0	0	0	0	0	0	0	0	2	6	6	5	0	0
China	0	0	2	1	1	16	25	49	69	113	136	135	125	139	142
Colombia	0	1	0	0	0	0	0	0	0	1	0	0	1	0	1
Cote Ivoire	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Croatia	0	0	0	0	0	0	1	0	0	1	2	1	1	1	0
Cyprus	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0
Czech Rep	0	0	0	0	0	0	0	1	1	5	4	7	22	10	10
Denmark	0	2	2	0	4	3	6	2	3	8	5	6	10	5	4
Egypt	0	0	0	0	0	0	1	0	0	0	0	2	0	2	3
Estonia	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1
Finland	0	0	1	0	0	2	2	2	2	6	12	12	16	6	10
France	3	2	3	1	9	7	20	23	27	29	37	55	56	63	52
Georgia	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0
Germany	2	3	14	11	16	15	35	42	30	68	86	66	78	73	87
Greece	0	0	1	0	0	0	2	2	2	7	7	5	15	5	10
Hungary	1	0	0	1	0	0	3	0	0	3	4	2	0	2	1
India	1	2	1	1	2	1	8	12	10	18	23	29	15	20	19
Indonesia	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0

Iran	1	0	0	0	1	0	0	2	2	6	4	6	7	4	2
Ireland	0	1	0	0	2	0	1	2	2	1	2	2	3	3	3
Israel	1	0	0	0	1	2	2	2	1	3	5	6	6	5	6
Italy	2	6	11	5	5	8	13	10	20	32	36	53	42	42	38
Japan	9	12	11	8	10	14	20	53	45	64	90	86	75	72	76
Jordan	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Kazakhstan	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Kuwait	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Kyrgyzstan	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
Latvia	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Lebanon	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Liechtenstein	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Lithuania	0	0	0	1	1	0	0	0	3	0	1	0	0	0	3
Luxembourg	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0
Malaysia	0	0	0	0	0	0	0	0	0	1	0	1	1	2	3
Mexico	0	0	0	0	1	4	7	1	12	7	9	9	10	11	6
Moldova	0	0	0	0	0	1	0	0	0	0	1	4	1	0	0
Morocco	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0
Netherlands	1	1	2	2	0	5	6	5	7	7	10	8	13	15	15
New Zealand	0	0	0	1	1	0	2	1	1	1	4	3	3	2	5
Nigeria	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Norway	1	0	0	0	2	0	0	1	0	1	1	4	4	0	2
Oman	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Pakistan	0	0	0	0	0	0	0	1	1	2	1	4	0	2	0
Peru	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Poland	1	1	0	0	1	0	5	2	5	4	13	11	9	4	9
Portugal	1	0	0	1	0	0	1	2	5	4	6	3	9	14	12
Romania	0	0	1	0	0	0	1	4	0	3	1	3	7	4	9
Russia	0	2	1	19	29	14	7	4	5	13	15	21	11	10	8
Saudi Arabia	0	0	0	0	0	0	0	0	0	1	1	0	2	2	3
Serbia	0	0	0	0	0	0	0	0	0	3	0	3	4	3	3

Serbia	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Singapore	1	0	1	1	2	2	8	10	12	16	17	22	19	20	20
Slovakia	0	0	0	0	0	1	1	1	0	0	1	0	0	7	1
Slovenia	0	0	0	0	0	0	0	3	5	2	4	2	3	0	1
South Africa	0	0	0	0	0	0	0	0	1	3	0	2	69	0	2
South korea	0	0	0	0	3	4	14	27	42	60	62	81	0	78	79
Spain	0	0	5	0	16	20	34	22	31	25	28	45	38	41	38
Sri Lanka	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Sweden	2	0	2	3	4	5	5	12	9	13	12	15	15	15	14
Switzerland	0	0	3	3	3	4	4	8	12	10	16	13	13	13	9
Taiwan	1	0	3	4	1	4	6	13	28	59	61	61	52	52	44
Tunisia	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Thailand	0	0	0	0	1	0	0	0	0	3	2	6	0	3	3
Tunisia	0	0	0	0	0	0	0	0	0	1	0	3	0	0	1
Turkey	0	0	0	0	0	0	0	1	1	1	4	6	5	8	9
UAE	0	0	0	0	0	0	1	1	0	1	1	1	0	0	1
UK	0	3	5	6	15	27	28	26	42	37	52	67	64	61	44
Ukraine	6	0	0	1	1	1	1	2	4	3	6	2	6	3	2
Uruguay	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
USA	0	20	33	12	30	41	67	98	123	173	191	216	233	225	211
Uzbekistan	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
Venezuela	14	0	0	0	1	1	2	0	1	0	0	1	0	0	0
Vietnam	0	0	0	0	0	0	0	0	0	1	0	2	2	1	1
Yugoslavia	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
Sum	48	57	106	89	172	220	366	476	608	896	1079	1203	1167	1159	1130

Appendix C Authors & coauthors

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
single	109	162	249	286	454	633	1128	1505	2191	3297	4173	4855	4611	4464	4493
multiple	29	38	52	60	92	123	270	361	540	918	1096	1208	1140	1051	1056

Appendix D Top Countries

Year	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
USA	0	20	33	12	30	41	67	98	123	173	191	216	233	225	211
China	0	0	2	1	1	16	25	49	69	113	136	135	125	139	142
Germany	2	3	14	11	16	15	35	42	30	68	86	66	78	73	87
S-Korea	0	0	0	0	3	4	14	27	42	60	62	81	0	78	79
Japan	9	12	11	8	10	14	20	53	45	64	90	86	75	72	76
France	3	2	3	1	9	7	20	23	27	29	37	55	56	63	52
Taiwan	1	0	3	4	1	4	6	13	28	59	61	61	52	52	44
UK	0	3	5	6	15	27	28	26	42	37	52	67	64	61	44
Canada	0	0	1	1	3	1	4	10	16	21	33	30	34	29	38
Italy	2	6	11	5	5	8	13	10	20	32	36	53	42	42	38
Total	17	46	83	49	93	137	232	351	442	656	784	850	759	834	811

Appendix E top cities

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
BEIJING, CHINA	0	0	1	1	0	15	13	41	75	154	143	141	101	113	85
SINGAPORE	2	0	2	1	2	4	11	25	40	91	97	102	73	58	63
SEOUL, SOUTH KOREA	0	0	0	0	1	3	5	26	31	77	61	90	107	123	116
TAIPEI, TAIWAN	0	0	0	0	0	0	0	7	16	54	41	58	79	39	66
HSINCHU, TAIWAN	0	0	0	2	1	0	2	5	26	59	53	57	55	57	26
SHANGHAI, CHINA	0	0	0	0	1	3	6	12	23	71	70	57	67	58	59
HANGZHOU, CHINA	0	0	0	0	0	1	2	12	6	16	22	48	21	25	27
HONG KONG, CHINA	0	0	0	0	0	3	0	9	27	45	37	45	22	10	22
TAINAN, TAIWAN	0	0	1	2	0	1	0	7	12	48	33	41	47	25	13
MADRID, SPAIN	0	0	1	0	14	21	23	14	27	9	21	41	29	24	11
total top top	0	0	0	0	0	0	0	0	0	0	0	230	0	0	0
total publications	48	57	106	89	172	220	366	476	608	896	1079	1203	1167	1159	1130

Appendix F Top 10 Cities per year

1997	1998	1999	2000	2001
IBARAKI, JAPAN	COVENTRY, UK	PALO ALTO CA, USA	ST PETERSBURG, RUSSIA	ST PETERSBURG, RUSSIA
PALO ALTO CA, USA	IBARAKI, JAPAN	MAYENCE, GERMANY	MOSCOW, RUSSIA	MOSCOW, RUSSIA
KANAGAWA, JAPAN	GENOA, ITALY	TEMPE AZ, USA	NOVGOROD, RUSSIA	MADRID, SPAIN
MOFFETT FIELD CA, USA	MOFFETT FIELD CA, USA	PASADENA CA, USA	GENOA, ITALY	NOVOSIBIRSK, RUSSIA
OAK RIDGE TN, USA	LIVERMORE CA, USA	MUNICH, GERMANY	SANTA BARBARA CA, USA	NOVGOROD, RUSSIA
MILAN, ITALY	OAK RIDGE TN, USA	SEATTLE WA, USA	IBARAKI, JAPAN	TOULOUSE, FRANCE
BUDAPEST, HUNGARY	LYNGBY, DENMARK	ROME, ITALY	MUNICH, GERMANY	BERLIN, GERMANY
LAUSANNE, SWITZERLAND	BERKELEY CA, USA	JENA, GERMANY	URBANA IL, USA	BARCELONA, SPAIN
TOKYO, JAPAN	CHIBA, JAPAN	ST LOUIS MO, USA	PASADENA CA, USA	STANFORD CA, USA
SINGAPORE, SINGAPORE	IKOMA, JAPAN	OSAKA, JAPAN	BERLIN, GERMANY	GOTHENBURG, SWEDEN
2002	2003	2004	2005	2006
MADRID, SPAIN	CAMBRIDGE, UK	BEIJING, CHINA	BEIJING, CHINA	BEIJING, CHINA
BEIJING, CHINA	MADRID, SPAIN	SEOUL, SOUTH KOREA	SINGAPORE, SINGAPORE	SINGAPORE, SINGAPORE
ST PETERSBURG, RUSSIA	BEIJING, CHINA	SINGAPORE, SINGAPORE	SEOUL, SOUTH KOREA	SEOUL, SOUTH KOREA
PISA, ITALY	SINGAPORE, SINGAPORE	HEFEI, CHINA	MADRID, SPAIN	SHANGHAI, CHINA
NOVGOROD, RUSSIA	HEFEI, CHINA	IBARAKI, JAPAN	HEFEI, CHINA	HSINCHU, TAIWAN
MIYAGI, JAPAN	CAMBRIDGE MA, USA	TAEJON, SOUTH KOREA	HONG KONG, CHINA	CHANGCHUN, CHINA
CAMBRIDGE, UK	OAK RIDGE TN, USA	KANAGAWA, JAPAN	HSINCHU, TAIWAN	TAIPEI, TAIWAN
SYDNEY, AUSTRALIA	CHANGCHUN, CHINA	MADRID, SPAIN	NANJING, CHINA	TAINAN, TAIWAN
NANJING, CHINA	KARLSRUHE, GERMANY	AICHI, JAPAN	SHANGHAI, CHINA	HONG KONG, CHINA
MOSCOW, RUSSIA	MAHARASHTRA, INDIA	COLUMBUS OH, USA	TAIPEI, TAIWAN	NANJING, CHINA
2007	2008	2009	2010	2011
BEIJING, CHINA	BEIJING, CHINA	SEOUL, SOUTH KOREA	SEOUL, SOUTH KOREA	SEOUL, SOUTH KOREA
SINGAPORE, SINGAPORE	SINGAPORE, SINGAPORE	BEIJING, CHINA	BEIJING, CHINA	BEIJING, CHINA
SHANGHAI, CHINA	SEOUL, SOUTH KOREA	TAIPEI, TAIWAN	SHANGHAI, CHINA	TAIPEI, TAIWAN
SEOUL, SOUTH KOREA	TAIPEI, TAIWAN	SINGAPORE, SINGAPORE	SINGAPORE, SINGAPORE	SINGAPORE, SINGAPORE
HSINCHU, TAIWAN	HSINCHU, TAIWAN	SHANGHAI, CHINA	HSINCHU, TAIWAN	SHANGHAI, CHINA
NANJING, CHINA	SHANGHAI, CHINA	HSINCHU, TAIWAN	NANJING, CHINA	TAEJON, SOUTH KOREA
CHANGCHUN, CHINA	HANGZHOU, CHINA	TAINAN, TAIWAN	TAIPEI, TAIWAN	LAFAYETTE IN, USA
TAIPEI, TAIWAN	HONG KONG, CHINA	IBARAKI, JAPAN	CAMBRIDGE MA, USA	TOKYO, JAPAN
HONG KONG, CHINA	TAINAN, TAIWAN	TAEJON, SOUTH KOREA	IBARAKI, JAPAN	IBARAKI, JAPAN
OAK RIDGE TN, USA	MADRID, SPAIN	GRENOBLE, FRANCE	TAEJON, SOUTH KOREA	CAMBRIDGE MA, USA

Appendix G Topics and Cotopics

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
singel	85	126	209	209	275	367	753	967	1224	1793	2131	2372	2159	2050	2061
multiple	16	21	38	30	58	99	246	342	502	844	990	1078	995	913	914

Appendix H Top ten Topics

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
GROWTH	1	2	4	3	9	12	38	49	89	179	169	170	145	122	122
NANOPARTICLES	0	1	0	1	1	5	13	26	50	95	115	146	129	110	124
FILMS	2	1	4	1	4	7	20	35	57	105	130	138	127	108	123
FABRICATION	4	2	4	0	2	3	17	33	60	93	127	120	126	99	100
NANOSTRUCTURES	0	2	1	2	1	3	7	9	33	72	77	93	81	75	69
ARRAYS	0	0	0	0	1	8	8	22	44	60	89	87	88	95	105
NANOCRYSTALS	0	0	0	1	4	5	6	10	34	78	71	84	83	55	52
NANOWIRES	0	0	1	0	3	4	8	26	50	93	97	81	69	60	59
THIN-FILMS	1	0	2	0	2	5	13	25	37	82	85	80	77	68	70
PARTICLES	0	1	1	0	1	5	12	26	31	60	55	80	49	63	41

Appendix I Departments

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Dept Phys	3	5	8	5	14	17	29	47	76	148	175	204	174	166	151
Dept Mat Sci & Engn	0	0	0	0	1	3	9	22	34	71	82	91	88	76	64
Dept Chem	2	1	2	1	3	8	14	34	65	101	93	90	112	89	69
Dept Mech Engn	0	0	3	4	2	1	5	16	24	37	40	62	44	36	35
Dept Elect Engn	1	1	3	4	6	6	8	14	18	48	32	46	49	42	45
Dept Chem Engn	0	0	0	0	3	1	5	5	43	28	33	41	36	25	27
Dept Elect&Comp Engn	0	0	2	1	0	2	5	12	6	18	34	29	8	36	48
Dept Phys & Astron	0	0	0	1	5	8	3	8	8	11	17	24	34	34	29
Dept Fis	0	0	0	0	0	3	4	8	7	8	16	12	16	8	10
Dept Engn Mech	0	0	0	0	1	0	1	4	4	4	9	10	2	9	4
Inst Phys	0	1	1	1	5	4	5	9	9	11	17	10	15	13	7

Appendix J International cooperation

Pub/yr	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
2	7	6	14	18	32	37	40	67	98	193	221	287	280	262	250
3	1	0	0	5	8	10	10	11	16	28	30	48	28	38	43
4	0	0	0	0	1	0	0	3	2	2	5	3	12	10	10
5	0	0	0	0	0	0	0	1	1	0	1	2	3	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Total	8	6	14	23	42	47	50	82	117	223	257	340	323	310	303

Appendix K triple helix organisations

	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
universities	21	26	56	55	84	130	195	266	332	497	570	651	620	604	595
companies	11	3	10	0	8	14	12	19	26	40	52	55	53	64	49
institutes	16	16	20	21	43	34	57	77	88	134	154	164	161	181	166