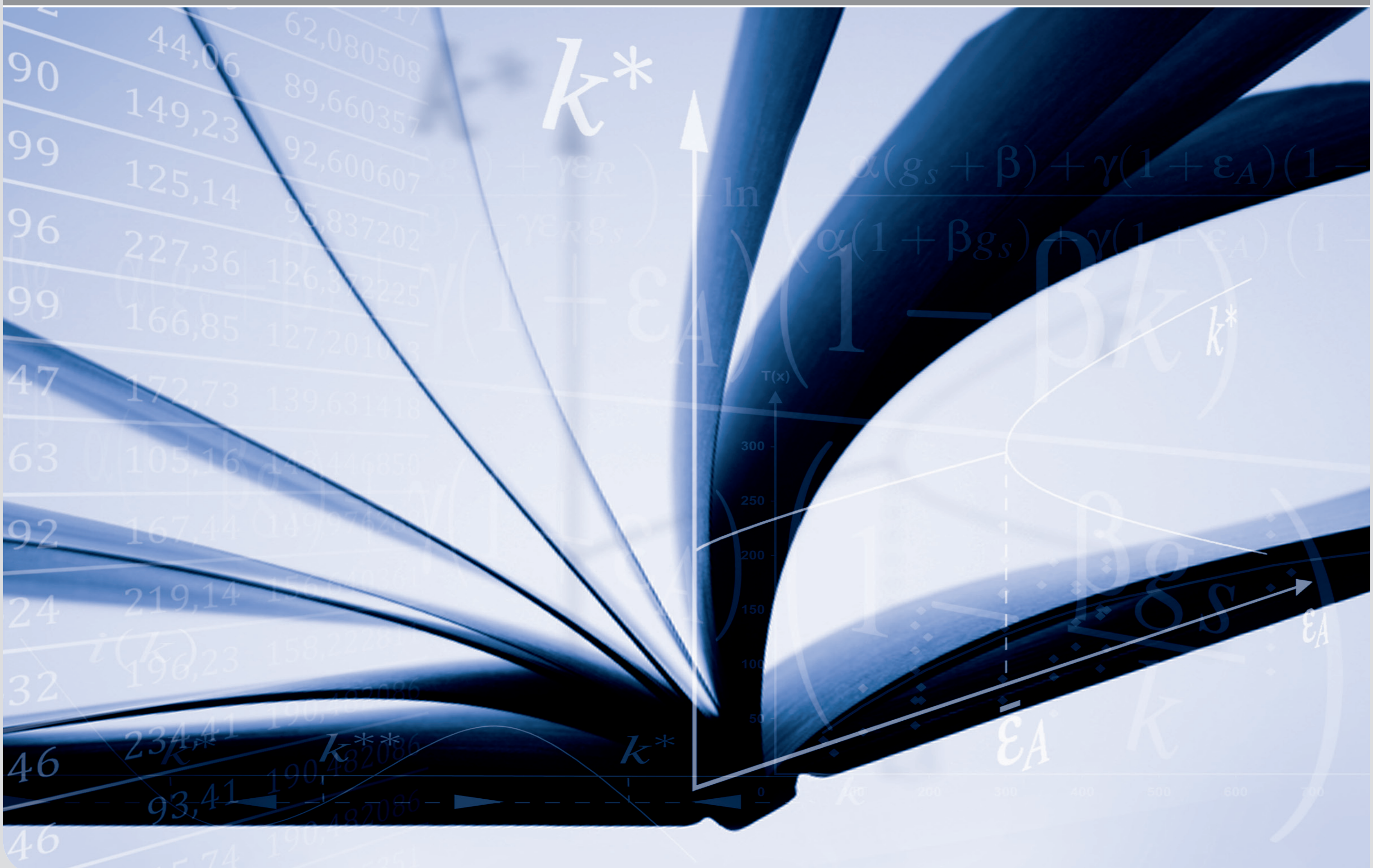
Karlsruher Institut für Technologie

On the role of general purpose technologies within the Marshall-Jacobs controversy: the case of nanotechnologies

by Nina Menz and Ingrid Ott

No. 18 | APRIL 2011

WORKING PAPER SERIES IN ECONOMICS



KIT – University of the State of Baden-Wuerttemberg and
National Laboratory of the Helmholtz Association

econpapers.wiwi.kit.edu

Impressum

Karlsruher Institut für Technologie (KIT)
Fakultät für Wirtschaftswissenschaften
Institut für Wirtschaftspolitik und Wirtschaftsforschung (IWW)
Institut für Wirtschaftstheorie und Statistik (ETS)

Schlossbezirk 12
76131 Karlsruhe

KIT – Universität des Landes Baden-Württemberg und
nationales Forschungszentrum in der Helmholtz-Gemeinschaft

Working Paper Series in Economics
No. 18, April 2011

ISSN 2190-9806

econpapers.wiwi.kit.edu

On the role of general purpose technologies within the Marshall–Jacobs controversy: The case of nanotechnologies

Nina Menz
Karlsruhe Institute of Technology (KIT) §

Ingrid Ott
Karlsruhe Institute of Technology (KIT) **
Kiel Institute for the World Economy (IfW)

April 8, 2011††

Abstract

This paper investigates the role of nanotechnologies as a general purpose technology for regional development. Due to pervasiveness, nanotechnologies may be utilized in diverse applications thereby providing the basis for both localization and urbanization externalities. We carry out patent and publication analyses for the city state of Hamburg during the period 1990-2010. We find evidence that nanotechnologies are advanced in the context of regional knowledge bases and follow up prevailing specialization patterns. As nanotechnologies develop both industry specific and city specific externalities become effective leading to specialization deepening and specialization widening which both are functions of the increasing nano-knowledge base.

Keywords: general purpose technology, nanotechnology, specialization, diversification, Marshall-Jacobs controversy, patent and publication analysis

JEL-codes: R11, O31

---

§nina.menz@kit.edu

**ingrid.ott@kit.edu

††The authors are grateful to valuable discussions with Jan Youtie and Ulrich Schmoch. Helpful comments from the participants of the NanoWinterSchool that took place in Pinsot/Grenoble in April 2011 are also acknowledged.

1 Introduction

Nanotechnologies are expected to largely dominate the coming decades by increased application in various fields. Moreover, it's widely accepted that nanotechnologies qualify as future dominating general purpose technology (henceforth GPT) (Youtie et al. 2008, Graham and Iacopetta 2009), which is characterized by *wide variety of uses, technological dynamism* and *innovation spawning*, resulting in *innovational complementarities* (Bresnahan 2010). Due to their capacity to spur a set of complementary innovations, GPTs such as nanotechnologies are expected to interact with other technologies along the value creation chain and thus to serve as engines of growth.

Within a regional context, spillovers that result from non-rivalry of the knowledge produced can have a positive impact on innovations. Since these spillovers are limited by geographical distance, Feldman (1994) suggests that especially innovative activity clusters spatially. As nanotechnologies as GPT entail a great variety of innovations it is reasonable to assume that they act as agglomeration forces in sectors already showing a tendency to cluster. However, the impact of different kinds of knowledge spillovers on innovativity and regional development is still an unresolved puzzle. Marshall-Arrow-Romer externalities are *industry specific*, as they point to the importance of close technological proximity and specialization of the knowledge spilling over in order to have a positive impact on the productivity of innovation in that particular industry (Glaeser et al. 1992). Contrariwise, Jacobs externalities are *city specific* and emphasize the role of diversity within the economic structure for fostering the recombination and diffusion of ideas, although a minimum degree of technological similarity is needed for complementary knowledge spillovers becoming effective (Jacobs 1969, Glaeser et al. 1992). While the empirical literature offers ambiguous findings concerning the relevance of these externalities' effects for knowledge-intensive industries, the particular role of the *Marshall* or *Jacobs* externalities in the context of the special features of GPTs (e.g. concerning pervasiveness or innovational complementarities) has – to the best of our knowledge – not yet been considered at all.

What is hence the role of diversity (in contrast to specialization) which is the immediate impact of pervasiveness of a GPT? To what extent is specialization, which is in sharp contrast to this pervasiveness, conducive to the development of GPTs by innovations? How can the resulting externalities be exploited successfully? Which role does the linkage and hence interdependence of innovation processes along the value creation chain due to innovational complementarities play? The development of hypotheses and indicators exploring these questions is hence what we set out to do in this paper. We detail these thoughts in the context of nanotechnologies as the expected most important GPT for the next several decades and within the region of the city of Hamburg, which is chosen as a level of analysis due to the property of being a city state, which is easily manageable but thereby not less informative than for a broader regional setting.

The GPT's pervasive character allows for its utilization in basically all imaginable and diverse applications. We hence assume both specialization and diversification as being important, which we indeed find for the case of Hamburg. However, since a certain degree of specialization is required for achieving state-of-the-art expertise that allows for leading edge innovations (Garcia-Vega 2006), we hypothesize nanotechnologies to be advanced in the context of already existing regional specialization patterns, which could also be found evidence for. Throughout the process of technology development it is moreover quite reasonable to assume that the development of the GPT will feed back to this specialized knowledge base and also influence the prevailing specialization structure by deepening and/or widening prevailing regional specialization patterns. And indeed we found evidence for a feedback mechanism between the development of nanotechnologies and regional development to exist insofar as the initial specialization is further deepened, but with decreasing intensity and as there is obviously at least a propensity for the regional nano-knowledge base to diversify.

The rest of this paper is organized as follows: In Section 2, the theoretical framework of knowledge-intensive innovations is sketched, with a special focus on GPT. Based on this, we derive the hypotheses in Section 3. Section 4 takes stock of nanotechnologies in Hamburg, already presenting basic results. We investigate the empirical evidence of our hypotheses in section 5 with respect to the emergence of specialization and diversification and within Section 6, focusing on their development. Section 7 briefly discusses the results and concludes.

2 Theoretical framework

2.1 Nanotechnologies as a general purpose technology

To quote from the homepage of the National Nanotechnology Initiative, "nanotechnology is the understanding and control of matter at dimensions of roughly 1 to 100 nanometers, where unique phenomena enable novel applications. Encompassing nanoscale science, engineering and technology, nanotechnology involves imaging, measuring, modeling and manipulating matter at this length scale."[1] Nanotechnologies are interdisciplinary

[1] http://www.nano.gov/html/facts/whatIsNano.html, retrieved on January 2011. Palmberg et al. (2009, p 19f) provide an overview on the definition of nanotechnologies by various other actors. The mentioned definitions all have in common that nanotechnologies involve purposeful manipulation (not nano by accident), size-dependent properties and functions as well as pervasiveness.

and combine various basic technologies thereby contributing to the convergence of up to now mostly isolated disciplines, e.g. physics and chemistry. Nanotechnologies are expected to be the dominating general purpose technology of the coming decades (Youtie et al. 2008, Graham and Iacopetta 2009). Bresnahan and Trajtenberg (1995), who coined the term GPT, characterize them as enabling technologies: They offer a generic function which can be used productively in a wide range of application fields. Being more precise, a GPT arises if a drastic innovation may be distinguished by the following three features: *Pervasiveness, technological dynamism (scope for improvement)* and *innovation spawning* as well as *innovational complementarities*, i.e. interdependent innovation processes along the value creation chain.[2] Pervasiveness is the consequence of a generic function thus allowing for the technology's application in a wide range of fields. These fields can be entirely different, as nanotechnologies can be employed, for instance, in making airplanes lighter without loss of stability, in drug delivery systems or in new generation solar cells. These various fields can in turn induce new application fields themselves, e.g. by innovation spawning. In nanotechnologies, the generic function stems from the possibility to rearrange atoms encompassing new properties, which can be used in effectively any technology. Through further development at every level of the value creation chain, the GPT may be improved continuously, e.g. by the reduction of size or increase of stability. When the quality of the GPT is improved, the downstream application sectors benefit of a better quality of the GPT as an intermediate input. As private returns to investment in R&D are increasing with the GPT's quality, the downstream sectors have an incentive to improve their technology as well. These interdependencies arise along the entire value creation chain. Moreover, the use of the GPT becomes profitable for other sectors and thus the GPT's range of use is widened. This process of innovation works upwards the value creation chain as well, as a wider range of use or a better downstream technology provides scope for improvement and commercial opportunities as incentives to innovate in the GPT sector thus displaying a market size effect. Profits in the GPT sector are in the same way dependent on the application sectors' technologies, leading to higher investments in R&D when a downstream technology is improved. These feedback effects describe the aforementioned innovational complementarities: Profits from innovations in the downstream sectors rise when the GPT is improved and vice versa both as a result of an increased productivity of R&D in the respective sector (Bresnahan and Trajtenberg 1995). Innovation spawning can be found in the existence of nano-enhanced value creation chains, consisting of initial, intermediate, and downstream innovations. Carbon nanotubes, embodied in nano-enhanced coatings and finally employed in a variety of final products, such as airplanes, nano-enhanced clothes, self-cleaning windows oxidizing organic matter, rotor

[2]For a further discussion of the characteristics that define a GPT, see also Lipsey et al. (1998) or more recently Bresnahan (2010).

blades or electronic displays can be identified as such (Lux Research 2006, Youtie et al. 2008), emphasizing at the same time the wide range of uses of nanotechnologies. An example for innovational complementarities can be found with the technology that made research on and progress with nanotechnologies possible and which is now an application sector of nanotechnologies itself: Electronic microscopy (Youtie et al. 2008, Palmberg and Nikulainen 2006). Likewise, this mechanism emphasizes the linkages between pervasiveness and technological dynamics of the GPT, resulting in a widespread technology with enormous growth potential. These potentialities are perceived by various actors that try to benefit from the development of the technology. Within this paper we argue that in order to understand the technology development one has to consider the interaction and especially the feedback effects between the technology and its regional and economic context.

2.2 General purpose technologies and the Marshall-Jacobs controversy

In order to get a better understanding of the advancement of a GPT one has to deal with the aforementioned characteristics of the technology but thereby emphasizing how the technology is embedded within the existing research and production environment. Then, basically two perspectives are of major importance: The industry-specific and the city-specific level. Their respective impact on a region's productivity is summarized within the so-called Marshall-Jacobs controversy. However, how this controversy is affected by the development and diffusion a GPT is still an unresolved puzzle.

industry-specificity: The productivity-enhancing effect of spatial proximity has already been brought up by Marshall (1890) and the concept has been further developed by Arrow (1962) and Romer (1986). The basic reasoning implies that local agents can share the same assets and benefit from goods and services provided by specialized suppliers as well as from a local labor market pool. Efficient communication as a consequence of face-to-face contacts builds up trust, promotes the development of networks, partnerships and joint projects and enables knowledge being diffused easily between the various actors involved along the value creation chain. Prevalently, the corresponding knowledge as well as the spillovers between the various actors refer to specialization and are hence *industry-specific*.[3] Utilizing these productivity gains enhances overall income thereby leading to larger markets, inducing labor mobility and also feeding back to production. If the mentioned effects are sufficiently large, they become self-reinforcing thereby acting as ag-

[3]In the literature these spillovers are also summarized by the term Marshall-Arrow-Romer (MAR) or as localization externalities. See Audretsch and Feldman (2004) or Brakman et al. (2008) for a further listing of spillover mechanisms.

glomeration forces that finally lead to spatial concentration of economic activity.[4] Spatial concentration is frequently accompanied by regional specialization and the emergence of clusters. Although there is still no overall consensus on a general definition of an industrial cluster, the term usually refers to a specialized network of firms and institutions thus including "[...] a geographically proximate group of inter-connected companies and associated institutions in a particular field, linked by commonalities and complementarities [...]" (Porter 2000, p. 254). Its functional principle relies on the advantages of spatial, technological, and cultural proximity and linkages across activities thereby increasing productivity of innovation and production processes and thus the resulting economic performance.

City-specificity: However, a different view emphasizes that the sole focus on specialization might be a misleading development strategy for a region. This line of argumentation is based on the concern that too much specialization may inhibit the emergence and evolution of new technological fields. In addition, lock-in effects are risked particularly with respect to the exchange between basically complementary but heterogeneous knowledge (Fritsch and Slavtchev 2008). This leads to the alternative estimation of the various agents' interaction and highlights the role and importance of so-called *city-specific* externalities:[5] Already Jacobs (1969) suggests that especially the diversity of the economic structure fosters the recombination and diffusion of ideas. Following this line of argumentation, the exchange of complementary knowledge across diverse firms and economic agents favors innovative activity, increases the stock of knowledge available to the individual firm and thus also strengthens the productivity of a certain region in which the firm is embedded. Arguably, the most important spillovers come from outside the respective industry.

Functional specialization and the clustering of innovative activity: Recent analysis in economic geography also distinguish sectoral and functional specialization of regions (Duranton and Puga 2005). While the former relate to the aforementioned industry specificity, the latter relies on the regional separation of management and production activities of multi-unit firms that result as a consequence of organizational change. Again the proximity-productivity relationship is the basic driver of this separation: Higher costs of centrality are only born by the actors if they may be justified by higher productivity as a result of increased productivity, e.g. due to face-to-face contacts. These considerations do not only arise in the context of management and production but also in the context of

[4] Although these basic relationships have been well-recognized for a long time, the seminal work of Krugman (1991) has provided the theoretical basis for an entire field in economics which now is labeled as the New Economic Geography (Brakman et al. (2009) provide an excellent overview).

[5] These are frequently also called urbanization externalities. Since both types of the discussed externalities refer to a certain location and thus are 'localized' to some extent, we prefer the notion in city-specific and industry-specific externalities.

research and development. Feldman (1994, pp. 93ff.) suggests that especially innovative activities cluster.

Due to proximity, agents can easily learn from each other, absorb knowledge spillovers within one industry and eventually innovate faster. The question arising in this context is the interaction between city-specific and industry-specific externalities. Tacit knowledge and spatially bound knowledge spillovers may hence be conducive for local collective learning processes (Maskell and Malmberg 1999). Also, the specialization of an industry in a region can stimulate R&D cooperations between firms or institutions sharing similar knowledge bases and thus induce a high level of knowledge spillovers between them and between others (Mowery et al. 1998). Put differently, proximity enhances the ability to exchange ideas, to sense new developments, to induce learning processes, to reduce uncertainty and to align R&D activities. This facilitates the generation and diffusion of innovations thereby also feeding back along the value creation chain. Between proximate actors, the marginal transmitting cost of knowledge is lowest due to frequent social interaction, hence communication and knowledge spillovers arise much more frequently than between remote ones (Venables 2006). Subsequently, proximity can be described as stimulative for innovations (Audretsch and Feldman 2004).[6] Hence, innovation activities locate where knowledge externalities reduce R&D–costs and increase the productivity of innovations. As a consequence, regions with specialized economic structures tend to be more innovative in that particular industry in fact along the entire value creation chain. This also applies to knowledge-intensive industries in general where technological spillovers are crucial since they are a major driver of innovative activity.

But also in the context of innovation activity, the argument of diversification and hence the importance of city-specific externalities becomes relevant. The reasoning for this is as follows: In diverse economies, the potential for an exchange of knowledge and ideas and the probability of random collisions of businesses are higher (Glaeser et al. 1992). More differentiated knowledge creates a greater variety of knowledge spillovers. An innovation working well in one industry often can be applied, modified and/or or further developed in other industries (Wu 2005). This phenomenon of *cross-fertilization* between basically different, but at least to some extent related technologies as well as even between (so far) unrelated technologies becomes more probable (Granstrand 1998, Suzuki and Kodama 2004, Garcia-Vega 2006). Firms can hence benefit from new technological possibilities and ideas and knowledge spilling over, stimulating innovative activity and preventing negative lock-in effects in one particular technology.

So far, the overall impact of industry-specific and city-specific externalities on regional

[6] The proximity to markets is important for innovation-intensive industries, too, as they constitute a testing ground for new products which can be developed following the needs of intermediaries/consumers. As this is not the focal point within this analysis, this aspect will not be explored in detail.

development is still an unresolved puzzle. This is especially true if one additionally focuses on the linkages between the various actors along the value creation chain or on the evolution of the relative importance of either externality across time. The discussion is usually captured by the term *Marshall-Jacobs controversy* thereby referring to the underlying industry-specific and city-specific externalities. Previous analyses do not provide an unambiguous solution to whether specialization or diversity in a region stimulates knowledge production and innovation activities. While Feldman and Audretsch (1999) find that diversity rather than specialization is important and Duranton and Puga (2000) support this view for the US, Paci and Usai (1999) still find ambiguous results for the case of Italy, where both externalities played a role in the innovations processes, with a tendency to more relevant specialization effects. Fritsch and Slavtchev (2008) conclude that specialization is important but only to a certain degree, further emphasizing the ambiguity. Meanwhile, van der Panne and van Beers (2006) argue that both externalities affect technological development but at different stages of the innovations process with specialization at the beginning and diversification rather at later stages. They hence contemplate the time dimension being relevant in this context as well. The focus of this paper goes one step further since it analyzes how the emergence of a GPT contributes to the Marshall-Jacobs controversy. Of major importance in this context are thus the following aspects:

In which contexts are GPTs developed and how does this feed back to prevailing specialization patterns? What is the role of diversity (in contrast to specialization) which is the immediate impact of pervasiveness? How does the relative importance of specialization and diversification evolve across time? What happens if innovation processes along the value creation chain are linked and hence interdependent, e.g. due to the aforementioned innovational complementarities?

3 Derivation of the hypothesis

Since a certain degree of specialization is required to achieve sufficient expertise for improving the state of the art of any technology, or put differently, for MAR externalities to become effective, it is quite reasonable to develop an emerging GPT along already existing specialization patterns. But such foci essentially come at the cost of a limited number of application fields. Moreover, considering the GPTs feature of pervasiveness, this restriction is not compulsory: Instead, it is the multi-purposeness of uses that induces continuous technological improvements thereby allowing for an even wider range of applications and thus exponentiating the GPT's inherent productivity effects. An increasing number of application sectors leads to higher innovation incentives in both the (upstream) GPT sector and the (downstream) application sectors. Due to innovational complementarities, the innovation processes along the value creation chain are interdependent, horizontal and vertical linkages between the various actors arise, and hence successful innovation feeds back in both directions (Bresnahan and Trajtenberg 1995).[7]

Basically, aside from the invention of new products and applications, the development of the GPT may also lead to an overlap between so far unconnected fields, e.g. via cross-fertilization that is most probably realized by effective Jacobs externalities. Ideas and innovations that initially have been developed for a particular use are presumably applicable in a broad variety of different fields as well.[8] Besides, GPTs entail a great variety of innovations and may become a relevant agglomeration force in those sectors that already show a tendency to cluster but where concentration is not yet prevalent. Thus, restricting the development of a GPT in the context of already existing specializations neglects the technology's inherent potential. It may even decrease the region's overall productivity of innovations elsewhere if feedback effects with other sectors and thus further innovations are impeded. Notwithstanding the existence of horizontal and vertical externalities, the innovation incentives are suboptimally low and thus innovations arrive too late and are too little. While we just mention this argument for the sake of completeness, Bresnahan and Trajtenberg (1995) detail it in their seminal paper.

Hence over time, specialization alone cannot be the optimal development pattern of nanotechnologies in regions, as diversification in the sense of broad applications promises respectable growth effects, too. Put differently: If specialization and diversification are both assumed to be conducive to the development of nanotechnologies by innovations in this field, hence if MAR and Jacobs externalities are basically relevant, how can these externalities be successfully exploited? Given a prevailing regional production structure, how does the regional nano-knowledge base (henceforth NKB) develop over time? As a proxy for this regional knowledge base we refer to two essential parts: The *scientific* knowledge that roughly serves as a measure for basic research outcomes and which is represented by publications whereas the *technological* knowledge reflects more applied research results and is approximated by patents.[9]

To get a deeper understanding one has to precisely analyze how the various individual actors (namely firms, research institutes, and universities) interact, develop and apply nanotechnologies in the context of the given regional structure, on the one hand, and how

[7]Bresnahan and Trajtenberg (1995) sketch these interdependencies by the metaphor of a technology tree. We adopt this logic and apply it to the development of nanotechnologies within the existing cluster structure in the city state of Hamburg in section 6. A graphical illustration is presented in Figure 4.

[8]For further readings see, e.g., Csikszentmihalyi (1997), Berkun (2007), Desrochers and Leppälä (2010).

[9]With this distinction we follow the delineation of regional knowledge bases as determined, e.g., by Avenel et al. (2007).

this structure is shaped by the overall development of nanotechnologies due to feedback effects, on the other hand. Basically, two features are imaginable over time: The development of nanotechnologies as a GPT begins with already existing specialization patterns that firstly are enhanced, e.g. by feedback loops or bigger market opportunities. In this sense, nanotechnologies are a source of *specialization deepening*, i.e. the strengthening of existing specialization patterns. At the same time, as the NKB increases it is natural that it also becomes broader. But then, already existing but so far isolated clusters might get tied together through the common use of the GPT and inherent cross-fertilization opportunities. This provides another source of specialization deepening within already existing clusters. Furthermore, due to the generality of purpose and the various vertical and horizontal linkages along the value creation chain, bigger advancements of the innovation might also have an impact on other and so far unrelated applications. This could make, e.g., so far latent clusters to become functional and cross-fertilization spread to new, formerly not concentrated industries. As a consequence, an additional cluster may emerge thus extending the existing specialization pattern. This phenomenon hence describes *specialization widening* since the amount of specialization within one region increases. Both seems to be likewise plausible and relevant in such a complex technology like nanotechnologies. Consequently, both specialization and diversification are important determinants of the development of nanotechnologies thereby reflecting the peculiarities of GPTs within the Marshall-Jacobs controversy. Notice that the following discussion mostly refers to the NKB and hence the innovation process that lies at the beginning of the value creation chain.

Summarizing the aforementioned discussion we derive the following hypothesis:

Hypothesis 1 *Emergence of specialization and diversification*
(a) Nanotechnologies are still in an early technological stage and are thus characterized by large technological dynamics.
(b) Due to the characteristics of pervasiveness both specialization and diversification may be observed.
(c) Nanotechnologies are mainly advanced in the context of already existing specialization patterns.

Hypothesis 2 *Specialization and diversification and the size of the NKB*
(a) Since NKBs firstly are developed in the context of already existing specializations, these patterns are strengthened (specialization deepening). As the increased NKB also becomes broader, formerly latent clusters may become functional. Then, additional clusters emerge (specialization widening).
(b) As the NKB evolves, the relative importance of specialization deepening decreases whereas the relative importance of specialization widening increases.

To carry out the analysis we focus on Hamburg's specialization pattern as well as on the development of the city state's NKB. The city state's level is well suited as level of analysis, as it has a manageable size in order to gain a good overview on the regional nanotechnology scene and to be able to develop indicators. At the same time, the city state level constitutes the hierarchy level NUTS 1, referring to a major spatial unit with better data availability and a single political administration. This is important as especially in Hamburg, which is not (yet) known, policy makers explicitly aim at developing a distinct nano cluster. However, the focus in this paper is not to analyze the distinct situation of nanotechnologies in Hamburg, but rather to gain first insights into the role of general purpose technologies within the Marshall-Jacobs controversy. The aim is hence an indicator-driven coverage and not a comparative assessment of the nano-scene in Hamburg.

In doing so we develop and apply several indicators to measure specialization and diversification as well as their evolution over time. In order to find out how nanotechnologies are characterized by specialization and diversification, how this responds to the regional economic structure and how the importance of specialization and diversification changes over time, a case study on the role of nanotechnologies and on their development was accomplished in the city state of Hamburg, Germany, in 2010. This allows us to contribute to the role of GPTs within the Marshall-Jacobs controversy in the context of a concrete region and for a concrete technology that due to its characteristics basically allows for the emergence of both specialization and diversification.

4 Nanotechnologies in Hamburg: Taking stock

Referring to the NKB, a publication analysis was conducted to gain information about the dynamics of the *scientific* knowledge whereas the implementation of applied nanotechnological research relies on *technological* knowledge as measured by patents. To get a deeper understanding of Hamburg's nano-scene as well as to better interpret the publication and patent data, archival and documentary data, including websites and analyses of the Hamburg chamber of commerce as well as of the Senate of Hamburg were used and the specialization pattern was investigated. Besides, some analyses of data of the official statistics are included.

Hamburg is Germany's second biggest city and one of the economically most prosperous metropolis with about 1.8m inhabitants and a GDP of about 90bn Euros in 2008 (Statistische Ämter des Bundes und der Länder 2008). The city state's economic structure is characterized by a sound industrial base and a well developed tertiary sector, both providing optimal conditions for ongoing success despite the challenges of structural and demographic change. The harbor ensures easy access to the world market which is es-

(Specialization)	Branch of economic activity	WZ	LQ
media	reproduction of recorded media	182	2.05
	retail sale of cultural and recreation goods in specialized stores	476	1.61
	publishing activities	58	2.32
	motion picture, video and television program production, sound recording and music publishing activities	59	3.04
	television broadcasting	602	0.46
aerospace industries	manufacture of air and spacecraft and related machinery	303	8.94
	air transport	51	1.54
maritime industries	fish processing	102	1.28
	manufacture of refined petroleum products	192	4.36
	building of ships and floating structures	301	3.57
	water transport	50	11.93
life sciences	manufacture of medical and dental instruments and supplies	325	0.67
	manufacture of soap and detergents, cleaning and polishing preparations, perfumes and toiletry	204	3.19
	manufacture of other chemical products	205	1.36
	manufacture of pharmaceuticals, medicinal chemical and botanical products	210	0.28
	manufacture of irradiation, electromedical and electrotherapeutic equipment	266	5.22*
	veterinary activities	75	0.44
	human health activities		0.82
aerospace industries, maritime industries, life sciences	R&D in science, engineering, agricultural science and medicine	721	0.95**

Table 1: Existing specialization in the city state of Hamburg, 2010, as per location quotients (LQs) and their assignments to clusters: media, aerospace industries, maritime industries and life sciences.
Branches according to the German Wirtschaftszweigklassifikation (WZ) and matching to the existing clusters. Own calculations based on data of the Bundesagentur für Arbeit (Statistik der sozialversicherungspflichtig Beschäftigten), March 2010, *data from December 2008.

pecially important for industrial production. It reflects first-nature geography advantages thereby providing the basis for specialization in maritime industries. Other specialization advantages in the secondary sector refer to aerospace industries and life sciences,[10] while specialization in the tertiary sector relies mostly on media.[11]

Basically there exist various indicators to measure concentration or specialization according to a given context.[12] Table 1 provides an overview on the recent economic structure in the city state of Hamburg as represented by relative employment shares. As measure serves the location quotient (henceforth LQ) which calculates the ratio between national and regional employment shares. We display the results for selected branches that are distinguished according to the German Wirtschaftszweigklassifikation (WZ), a classification system that is similar to the international standard industry classification (ISIC).[13] The left column in Table 1 highlights how the various branches may be assigned to the already well established clusters media, aerospace industries, maritime industries, and life sciences. A LQ > 1 indicates that employment in the respective branch is above national average thus displaying regional specialization.

The nano-scene is also shaped by some protagonists which include private firms, universities, and research institutes but also explicit nano institutions: One of the central nano research institutions in Hamburg is the Center for Applied Nanotechnology (CAN) that focuses its activities on nano applications in life sciences. The CAN has been co-founded as a public private partnership by industrial enterprises in 2005.[14] Since then, the CAN is concerned with life science topics in three (of altogether four) foci: Cosmetics, medicine and pharmacy; partnerships with private firms exist with enterprises that are also strongly related to life sciences[15]. Another important nano institution in Hamburg, namely the interdisciplinary nanotechnology center Hamburg (INCH) strongly focuses on basic research and states its key activity likewise as the connection of nanotechnologies and life sciences. Besides, the nano-industry is often considered as being part of the already existing life science cluster (Handelskammer Hamburg 2006). Some of these firms in Hamburg that

[10] Notice that there is no clear cut delineation of life sciences within the official statistics. However, it is broadly accepted that life sciences encompass biotechnology, pharmacy, cosmetics and medical engineering.

[11] These clusters are also well promoted by the regional economic policy (see e.g. Handelskammer Hamburg (2006) or http://metropolregion.hamburg.de/karte-clusterinitiativen).

[12] For instance, Paci and Usai (1999), Beaudry and Schifferauerova (2009); Palmberg et al. (2009) mention some indicators that are relevant in the context of nanotechnology.

[13] For further information on the WZ classification see http://www.destatis.de/. More information on ISIC can be found on http://unstats.un.org/. Notice that according to the LQ more specializations could be identified for the city state of Hamburg. Within this paper we restrict the discussion to those specializations that to our understanding refer to nanotechnologies and neglect the others. A recent and exhaustive overview of specialization in the city state of Hamburg is presented by Boje et al. (2010).

[14] Further information can be found at www.can-hamburg.de/company/background.php.

[15] Industrial partners are Beiersdorf AG, Eppendorf AG, Merck KGaA and BODE Chemie GmbH, see www.can-hamburg.de/company/network.php.

pursue various nano activities are displayed in Figure 5.

Data collection: As argued before, Hamburg's NKB includes publications and patents. For the following analysis, data of nano patents applied for between 1990 and 2009 was obtained from the German patent information system (DEPATIS) provided by the German Patent and Trade Mark Office (DPMA), accessed in October/November 2010.[16] For the period 1992-2009, we identified 383 patents related to nanotechnologies which were either applied for or developed by 98 different actors located in Hamburg.[17] Both invention and application of nano-patents refer to local nanotechnological competence. The further analysis also considers how each patent is assigned to one or more patent classes according to the International Patent Classification (IPC) system[18] at the 3 digit level in order to assure that we count different technological fields and to get an impression of possibly existing pervasiveness. The considered nano-related publications stem from Hamburg and are indexed in the Thomson-ISI 'Web of Science' database. Here we rely on the period between 1990 and 2009, where we identified 1169 publications with at least one contributor who is related to Hamburg.[19] Referring to publications, the distinction of technological fields is based on the definition of Thomson ISI subject areas assigned to the publication by the Web of Science.

[16]As at that point in time, data for 2010 was not complete, we chose to consider patents applied for until 31.12.2009. We used a boolean search query containing the same keywords we used for the publication search in German. For further information on the database see the Appendix B. This database has the advantage to show all applications for patents stemming from Germany. Patents applied for directly at the World Intellectual Property Organization (WIPO) are archived as well. But as these have to be converted into national rights in order to be protected in Germany, it is impossible to distinguish between patents of the same patent family, i.e. several patents that protect the same invention. This is why we chose to only consider German document data, indicated for by the prefix DE. We are hence aware of the fact that we miss the potentially valuable patents filed directly at EPO/WIPO and not yet concerted into German document data. Nevertheless, the chosen strategy increases the probability of including patenting by (small) domestic inventors (see also Palmberg et al. (2009)).

[17]As there was no nano-patent applied for in 1991, we only consider subsequent years until 2009.

[18]The International Patent Classification (IPC), established by the Strasbourg Agreement 1971, provides for a hierarchical system of language independent symbols for the classification of patents and utility models according to the different areas of technology to which they pertain. For further information, see World Intellectual Property Organization (n.d.).

[19]Again, we used a boolean search term in order to identify nano-related publications by searching for certain keywords thereby excluding other keywords in the topic of the paper. Further information on the database is again given within Appendix B. Notice that due to limited access to the publication data we are not able to identify the exact number of those actors and/or institutions that contributed to the 1169 publications.

5 H1: Emergence of specialization deepening and widening

As argued before, nanotechnologies are still a very young technology and also in Hamburg its development is promoted by various actors. We argue that during the advancement of the technology, the actors tie in - at least to some noticeable extent - with the existing economic structure. Recall that the hypothesis derived in Section 3 will be discussed with respect to the NKB. We incorporated the other information on the nano-scene in order to interpret the results

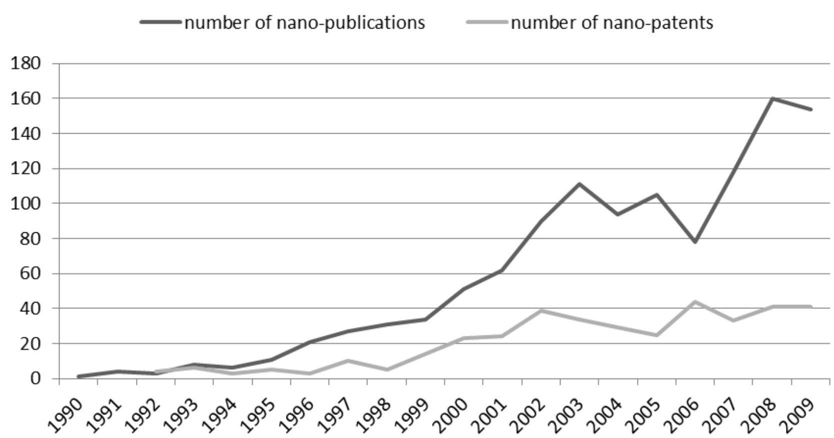
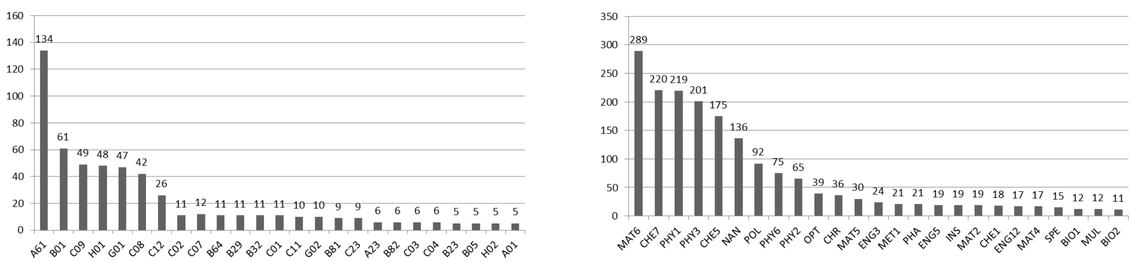


Figure 1: Development of the nano knowledge base in Hamburg

H1a: Figure1 illustrates how the technological and scientific NKB in Hamburg has grown during the last two decades. It highlights the primarily modest increase in the first decade which has been followed by a large rise during the last ten years. The large technological dynamics inherent in the development of nanotechnologies induces innovation spawning and is hence mirrored by an immense increase of the NKB within the last two decades. This pattern displays at a regional level the development of nanotechnologies that might be observed across all industrialized countries (for a comparison see Palmberg et al. 2009).

H1b: Taking a closer look at the composition of publication and patent fields it becomes obvious that both specialization and diversification of the NKB may be observed (see Figure 2): In total, the 383 patents refer to 71 different IPC classes and thus cover a large variety of application fields hence displaying diversity. If one also considers multiple assignments of one patent to various IPC classes these sum up to a total quotation of 640 IPC classes fo the 383 patents again highlighting the feature of diversity. But at the same time one might observe specialization. For instance, it becomes obvious that 134/640 and hence 21 % of patents quote one single IPC class, namely 'medical or veterinary science or hygiene' (IPC class named A61). Thus, specialization has to dimensions: Among the 134 patents quoting IPC class A61, there are patents exclusively assigned to A61 and patents that quote other IPC classes as well.

Figure 2(a) clarifies for the 25 most cited IPC classes that both issues of specialization and diversification may be observed: There is a large number of mentioned IPC classes which displays breadth/diversity, but at the same time one might also observe concentration in some of them. An analogous result arises in the context of publications, where again each single publication may be assigned to various subject areas. The 1169 nano publications stemming from Hamburg cover altogether 72 different Thomson ISI subject areas thus reflecting very diverse fields. But one might again observe that there are only a few subject areas where most of the publications concentrate. Again both features of specialization and diversification become prevalent (see Figure 2(b)).



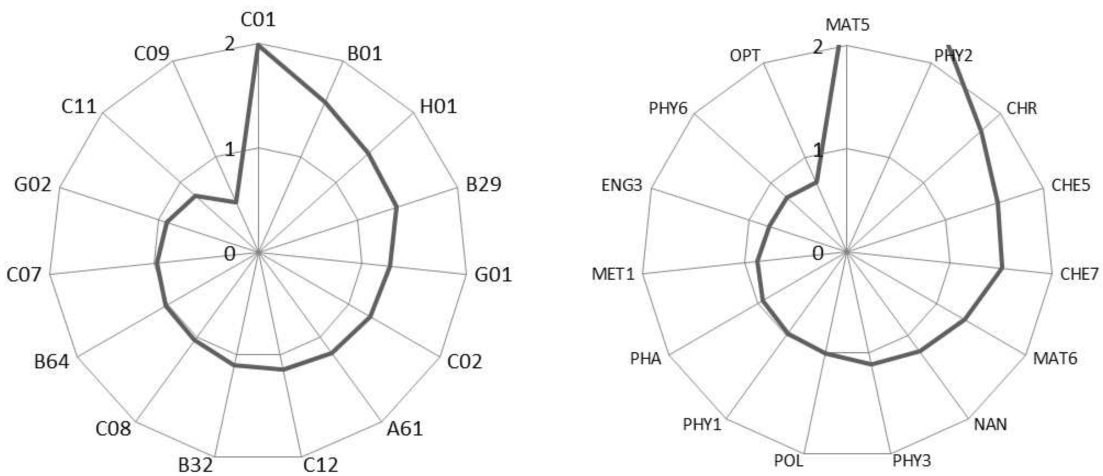
(a) number of patents per IPC class (top 25); includes multiple assignments of a patent to IPC classes

(b) number of publications per subject area (top 25); includes multiple assignments of a publication to subject areas

Figure 2: Specialization and diversification of the NKB in Hamburg (see tables 5 and 4 for decoding of the labels for the IPC classes and the subject areas)

H1c: The specialization of the economic structure as presented by the LQs within Table 1 also mirrors the recent economic policy in Hamburg that supports clusters in the fields of life sciences, maritime as well as aerospace industries, and media. Among these clusters, life sciences is by far the most important application field of nano-activated products, including nano-materials, nano-tools or nano-particles in general. Hence one might observe not only specialization of nanotechnology activity but one might assign this activity to an already existing cluster.

Figure 2(a) displays the distribution of patents into technological fields and shows that A61, encompassing with medicine, veterinary science of hygiene only life science applications, is by far the most frequently quoted IPC class (21%). With respect to publications, the relevant application fields are not as obvious as the subject areas they are assigned to mainly refer to classical sciences rather than technological application fields. Nonetheless, the most relevant fields (such as materials science (25%) and physical chemistry (19%) or applied physics (19%) concern nano-knowledge that is relevant in life sciences R&D (see figure 2(b)).



(a) compatibility of nano-patents to regional technological specialization pattern

(b) compatibility of nano-publications to regional scientific specialization pattern

Figure 3: Compatibility of nano-knowledge to already existing regional specialization patterns (see Tables 5 and 4 in Appendix B for decoding of the labels). Data referring to the aggregated scientific and technological NKB from 1990-2009. Index values equaling unity are indicating a nano-specialization corresponding to the overall specialization in that field in Hamburg. Values <1 refer to a nano-specialization below the overall specialization in this particular field. Values > 1 refer to a nano-specialization above overall average, indicating expected potential of the respective subdomain.

Another viewpoint focuses on specialization that is related to the existing research and development structure, e.g. by measuring compatibility of nano to overall publishing, respectively patenting, activity. This may be illustrated by calculating the so called Revealed Technological Compatibility (henceforth RTC) index.[20] It displays to what degree nanotechnology publications and patent applications from Hamburg across different technological fields correspond to the city state's overall scientific and technological specialization profile. Figure 3 illustrates index values for the top 15 IPC classes quoted by patents filed

[20]The RTC index is adopted from the Revealed Technological Advantage (RTA) index which is frequently used to measure specialization within trade theory (Almeida 1996). Similarly to the LQ, the RTC index calculates the ratio of the share of the number of nano-patents (nano-publications) in the respective 3 digit IPC class (subject area) relative to the overall number of patents (publications) in this IPC class (subject area) in Hamburg and the respective shares in Germany.

from Hamburg. A value close to unity indicates that the considered specialization profile in nanotechnology application fields is similar to the overall technological specialization, i.e. this reflects links to existing research and development structures. RTC values significantly larger than 1 instead indicate application fields towards which much research activity is directed, which might suggest that the actors expect important future markets in this field.[21] Figure 3(a) highlights that about one half of the technological nano-applications in Hamburg coincide with the existing specialization pattern. A similar picture is drawn in Figure 3(b) which highlights compatibility of the scientific knowledge: In about one half of the top 15 subject areas, the specialization of nano-research corresponds to the overall scientific specialization profile in Hamburg, as RTC values are close to unity.

These index values suggest that pre-existing scientific as well as technological specialization patterns significantly shape the relevant application fields of GPTs. This is especially true for the existing cluster structure in Hamburg, shaping the regional development of nanotechnologies. For instance IPC classes A61 ('medicine'), C07 ('organic chemistry'), C08 ('organic macromolecular compounds') and C12 ('biochemistry') can be widely assigned to the field of life sciences, as well as B64 ('aircraft') surely refers to the aerospace industries. All these classes exhibit RTC values close to unity. As argued before, this mapping is more difficult for publications subject areas, but nonetheless the values for POL ('polymer science') and PHA ('pharmacology') form part of life sciences and are close to unity as well.

One might conclude that these findings basically support hypothes1s 1: The NKB has significantly increased within the last two decades, both features of specialization and diversification may be observed, and nanotechnologies advance in the context of already existing specialization patterns. With respect to Hamburg it becomes obvious that not all clusters are equally affected by the development of nanotechnologies but there is a strong bias in favor of life sciences.

[21] Obviously, this is the case for the subject areas MAT5 (materials science, composites) PHY2 (physics, atomic, molecular & chemical) and CHR (crystallography) as well as for the IPC classes C01 (animal or vegetable oils [...]) and B01 (physical or chemical processes or apparatus in general). For micro-technology, this index value supports the thesis that nanotechnologies open up new opportunities towards miniaturization and the sustainment of Moore's Law, for materials science this hints to the relevance of nano-materials as intermediary for the overall development of nanotechnologies. Hence high RTC values might also be a slight indicator for future emerging clusters.

6 H2: Specialization deepening and widening over time

Figure 4 stylizes within a technology tree for Hamburg how nanotechnologies as a GPT rely on the existing clusters life sciences, maritime and aerospace industries.[22] This figure also includes the slightly observable cluster of renewable energies which is important within the metropolitan area of Hamburg but not within the city state.[23] The figure illustrates the already huge variety of interdependencies of actors along the value creation chain and displays both horizontal and vertical linkages among the various upstream and downstream industries. We argue that these connections have manifold impacts on the specialization patterns: (i) already existing specializations are strengthened in the context of isolated clusters (specialization deepening as a consequence of MAR externalities), (ii) cross-fertilization induces interaction between so far isolated clusters which also deepens existing specializations (specialization deepening as a consequence of Jacobs externalities), and (iii) cross-fertilization also enables so far latent clusters to become functional (specialization widening as a consequence of both Marshall and Jacobs externalities).

H2a: The aforementioned degree of nanotechnological specialization in the life science sector in Hamburg is presumably needed in order to achieve the expertise that is necessary when aiming to improve the state-of-the-art techniques in such a complex technology (Garcia-Vega 2006). The application of nanotechnologies in this field thereby deepens the existing regional specialization pattern while contrariwise the specialization on life sciences at this stage of development surely drives the innovative activity of nanotechnologies. This reflects the feedback effects between upstream and downstream sector and also provides an example for specialized innovation spawning which leads to specialization deepening from the viewpoint of a single cluster.

Moreover, there exists a second dimension of specialization deepening, as nanotechnologies as connecting interface are also a starting-point of possible cross-fertilization effects, for instance in the development of nanoparticles for different applications (Henn 2008, p. 110). Nanotechnologies may hence also lead to an overlap between so far unconnected specialized clusters which then have the very same upstream sector of nanotechnologies in common and can possibly benefit from cross-fertilization effects. The research on nanomaterials in Hamburg for example is not only interesting for applications in life sciences. Composites that, thanks to nanotechnologies, combine old with new features (like stability and lightness with conductivity) are not only interesting in medicine (like for artificial replacements), but also for the endowment of airplanes (Airbus S.A.S. 2007). Nanoparticle research could be used as platform, originating nanoparticles with partly the same and

[22]Within Figure 4, the cluster 'media' is neglected since there is no obvious link to nanotechnologies at this stage of technology development.

[23]This is why no LQ values for renewable energy industries are available yet.

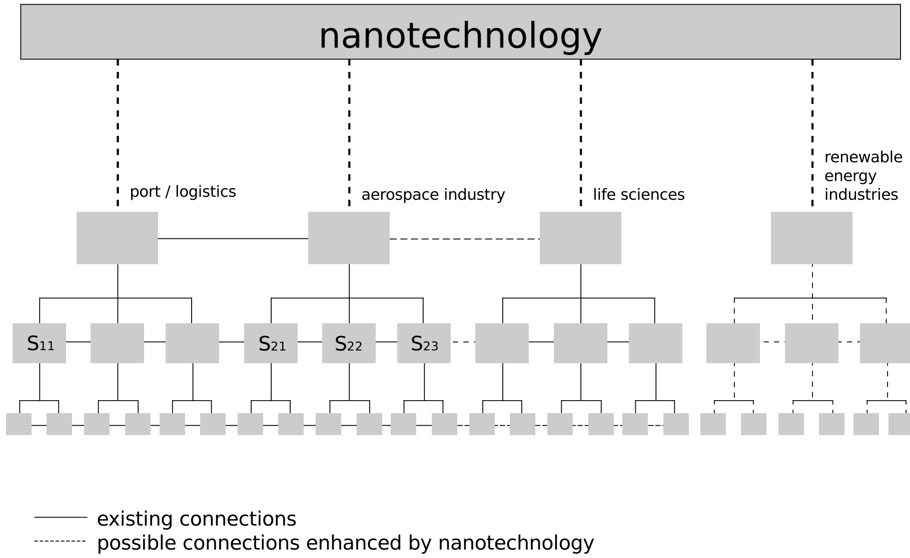


Figure 4: Technology tree of nanotechnologies in Hamburg, displaying the relationship of nanotechnologies to the economic structure; adopted from Bresnahan and Trajtenberg (1995)

partly differing features, depending on the later application. An improvement of quality and technology levels of nanomaterials as well as nanotechnologies in general (basing on the feedback mechanism of innovational complementarities) is due to increased research activity, learning and cross-fertilization effects. Besides, the joint use of several cluster structures at the same time opens cluster advantages for other application sectors, in total exponentiating the positive effects for the development of nanotechnologies. In Figure 4, this effect of cross-fertilization between so for unconnected clusters is indicated by the dashed line between aerospace and life sciences.

The possibility of cross-fertilization is not easily made visible. However, Figure 5 provides some evidence that there are several firms in Hamburg that apply for nano-patents with reference to the same IPC class, although stemming from different industries. This overlap could be a possible originator of cross-fertilization.

specialization widening: Finally, nanotechnologies as a GPT could possibly enhance connections to other potential clusters in Hamburg, as their generality of purpose makes them applicable virtually everywhere and subsequently strengthen developments there. The opportunity of cross-fertilization for instance also exists for renewable energies, where another kind of the mentioned composites could be used in rotor blades of wind wheels. To quote another example, employing nanomaterials, new solar cells could be developed by utilizing nanotubes in combination with quantum dots which has already been tested at Hamburg's research institutes. These quantum dots were afore applied in pharmaceutical applications. By improving the opportunities and shaping the structures of latently existing cluster structures, nanotechnologies are potentially able to induce a specializa-

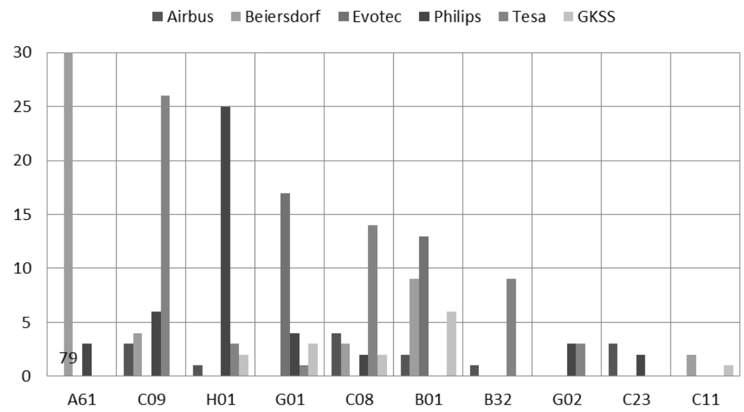


Figure 5: Overlapping IPC classes of most actively patenting firms in Hamburg as indicators for cross-fertilization

tion widening of both regional economic structure and the application fields of nanotechnologies. This interplay of existing and new structures and nanotechnologies is finally implemented in Figure 4 by mentioning also the cluster of renewable energies.

This presumed (future) structure is developed due to rather qualitative findings on the pattern of nanotechnological competencies and development in Hamburg. However, these qualitative results do support our hypotheses concerning the role of the regional economic specialization pattern: Nanotechnologies are specialized where Hamburg's regional industry is specialized, conveying compatibility of nano-specializations and the existing production as well as research and development structure. Furthermore, existing specialization is strengthened with the development of nanotechnologies insofar as so far isolated fields, such as e.g. aviation and maritime industries, became related via nano applications. Specialization widening seems to be plausible with respect to renewable energies.

H2b: So far the argumentation refers more or less to what is frequently called 'anecdotic evidence'. In what follows we support the argumentation by appropriate measures. This is done in the context of hypothesis 2b that focuses on the evolvement of specialization deepening and widening over time. To the best of our knowledge, at least some of the chosen indicators have not yet been applied to the regional level but are borrowed from other contexts of the literature, e.g., industrial organization or international trade. Our argumentation is most closely linked to the discussion of Avenel et al. (2007) who analyze NKB at a firm level. We bring their approach forward to a regional level to analyze the concepts of specialization deepening, on the one hand, and specialization widening, on the other hand as well as their evolution over time.

Again, the regional NKB which sums up all publications and patents of the nano actors within the city state of Hamburg during the last two decades and the underlying subject areas and IPC classes serve as basis for the analyses. In order to identify specialization, the well known concentration measure of the Hirschman-Herfindahl Index (HHI) is used. Applied to this paper, specialization thus measures to which extent publications (patents) are concentrated within subject areas (IPC classes). This index yields values within the interval of zero and unity with higher levels indicating higher degrees of specialization. In what follows we call the corresponding variable *depth*. Specialization deepening arises if the value of this index increases over time.

In contrast to this is an indicator that measures diversification or *breadth*. Notice that breadth is not just the opposite of depth but is represented by an additional indicator that provides information on how many subject areas (IPC classes) are assigned per publication (patents) on average. The resulting values are equal to or exceed unity with higher values indicating more breadth since then a single publication/patent becomes more useful in more fields or applications.

	Variable	N [years]	Mean	Median	Min	Max
Scientific NKB	Size	20	58.45	42.5	1	160
	Breadth	20	1.56	1.54	1.00	1.97
	Depth	20	0.17	0.09	0.06	1.00
Technological NKB	Size	18	21.27	23.5	4	41
	Breadth	18	1.60	1.59	1.25	2.10
	Depth	18	0.17	0.14	0.07	0.34

Table 2: Overview on variables and measures, underlying data bases: 1169 publications and 383 patents, 71 different IPC classes, 72 different Thomson ISI subject areas

Contributing to the Marshall-Jacobs controversy, the goal of the following part of the analysis is to better understand how the NKB of the city state in Hamburg develops, not only with respect to time and size but in this context concerning breadth and depth.[24] In doing so we carry out an empirical analysis for the period 1990–2009 with respect to publications and 1992–2009 concerning patents.[25] Recall that the development of the size of the NKB is already illustrated in Figure 2. Table 2 gives an overview on the parameters size, depth, and breadth for both scientific and technological knowledge. Figures 6(a) and 6(b) illustrate how breadth and depth evolve over time with the former increasing and the latter decreasing.

A Spearman correlation analysis shows that there is a positive and strongly significant

[24]Alternatively it is possible to calculate breadth and depth at the firm level. This does not allow for a proper analysis of how the values evolve over time as individual firm's NKB are to small (yet).

[25]Recall that only patent data after 1991 has been used for the analysis.

(a) scientific NKB (b) technological NKB

Figure 6: Depth and breadth of the nano knowledge bases over time in Hamburg

correlation between year and size of the NKB.[26] This allows us to analyze the impact of depth and breadth on the size of the NKB and to interpret the results in the context of varying importance of specialization (MAR externalities) and diversification (Jacobs externalities) as the NKB evolves.

variable	coefficient (standard error)	sign.	adj. R^2	F	obs
size of *scientific KB* (logs)			0.642	0.000	20
depth publications	-1.515 (0.458)	0.004			
breadth publications	0.879 (0.373)	0.031			
constant	0.365 (0.634)	0.572			
size of *technological KB* (logs)			0.437	0.005	18
depth patents	-4.045 (1.060)	0.002			
breadth patents	-0.483 (0.319)	0.151			
constant	2.620 (0.634)	0.001			

Table 3: OLS regression results: Size of the NKB in logs as function of breadth and depth separated for patents and publications

Table 3 summarizes the results of a simple multiple linear regression that analyzes how the size of both the scientific and the technological knowledge base are shaped by breadth and depth. It becomes obvious that for both publications and patents depth becomes less important as the NKB increases; both coefficients are negative and significant at the 1% level. Contrariwise, at least for the scientific NKB, breadth becomes more important as

[26] The resulting values are significant at the 1% level and exhibit the values of 0.913 for publications and 0.975 for patents.

the coefficient is positive and significant at the 5% level. However, the impact of breadth on the size of the technological NKB is not significant. Hence, specialization deepening and specialization widening do change with time passing by. Due to high correlations between time and size we assumed the size of the respective NKB to be important in this respect. Thus, with an evolving NKB, the relative importance of specialization deepening decreases whereas the relative importance of specialization widening increases. The latter is only supported here for the scientific NKB. The non-significance of breadth within the technological NKB might be due to a time lag between scientific achievements and their implementation in technology. It might hence be possible that the importance of breadth in technology still becomes important also for patents. So far, hence, hypothesis 2(b) can only be supported in what concerns the decreasing relevance of specialization deepening. For the increasing relevance, the results are ambiguous. However, due to very few observations, hypothesis 2(b) should not be rejected either.

7 Conclusions

This paper analyzes the role of specialization and diversification in the context of nanotechnologies as an emerging GPT. As such they are basically applicable in any context which requires a careful look at their embedding in existing value creation chains and the feedback loops induced by an improvement of that technology. We emphasize the different roles of specialization and diversification from both a static and a dynamic perspective. Applying these considerations to a dynamic setting, we develop the concepts of *specialization deepening* thereby referring to strengthening existing specialization patterns and *specialization widening* which describes the emergence of additional specializations. While the former concept is mainly based on industry-specific (or MAR) externalities the latter refers to city-specific advantages (or Jacobs externalities). We argue that over time the relative importance of specialization decreases whereas diversification increasingly gains importance. In doing so we develop and apply a set of indicators which are based on the technological and scientific NKBs as reflected by patent and publication activities. The analysis is carried out for the city state of Hamburg and includes data from the last two decades.

The main results may be summarized as follows: The strong increase of the NKB reflects the dynamism of this still young technology. Both patents and publications exhibit the characteristics of specialization on the one hand and diversification on the other hand both of them changing over time. Hamburg's nanotechnological competence emerges and develops where the existing regional economic structure already exhibits specialization advantages thereby mainly tying in with the already well-established cluster of life sciences. This is interpreted as reflecting the existence of industry-specific advantages (MAR externalities).

Such a docking is neither obvious per se nor compulsory as GPTs are characterized by pervasiveness. Empirical analysis shows that over time the relative importance of specialization significantly decreases for both patent and publication activity. The underlying specialization deepening probably results from compatibility of nanotechnological research and development activities in the sense of strengthening already existing regional advantages. Besides, it is quite probable that the pervasive character of nanotechnologies allows for cross-fertilization of so far unconnected clusters, thus inducing an additional impulse to strengthen existing specialization patterns. In contrast to this, the relative importance of diversification increases, but a significant effect can only be shown in the context of publications. We interpret this as reflecting the fact that diversity is not yet relevant in applied research. Future research would hence further have to investigate this empirically in the context of a larger database as well as to inspect the above results for other regions.

One might conclude that both Marshall as well as Jacobs externalities gain importance in the context of the development of nanotechnologies as a GPT. Over time their relative importance changes.

References

Airbus S.A.S.: 2007, Flying by nature, Blagnac.
URL: *www.airbus.com/store/mm_repository/pdf/att00011423/media_object_file_gmf_2007.pdf*

Almeida, P.: 1996, Knowledge sourcing by multinationals: Patent citation analysis in the US semiconductor industry, *Strategic Management Journal* **17**, 155–165.
URL: *www.jstor.org/stable/2486997*

Arrow, K. J.: 1962, The economic implications of learning by doing, *The Review of Economic Studies* **29**, 155–173.

Audretsch, D. and Feldman, M.: 2004, Knowledge spillovers and the geography of innovation, *in* J. Henderson and J. Thisse (eds), *Handbook of Regional and Urban Economics: Cities and Geography*, Vol. 4, Elsevier, Amsterdam, pp. 2713–2739.

Avenel, E., Favier, A., Ma, S., Mangematin, V. and Rieu, C.: 2007, Diversification and hybridization in firm knowledge bases in nanotechnologies, *Research Policy* **36**, 864–870.

Beaudry, C. and Schifferauerova, A.: 2009, Who's right, Marshall or Jacobs? The localization versus urbanization debate, *Research Policy* **38**(2), 318–337.

Berkun, S.: 2007, *The Myths of Innovation*, O'Reilly Media Inc., Sebastopol.

Boje, A., Ott, I. and Stiller, S.: 2010, Metropolitan cities under transition: The example of Hamburg/Germany, *Managing Global Transitions* **8**(4), 327–352.

Brakman, S., Garretsen, H. and van Marrewijk, C.: 2008, Agglomeration and government spending, *in* S. Brakman and H. Garretsen (eds), *Foreign Direct Investment and the Multinational Enterprise*, MIT Press.

Brakman, S., Garretsen, H. and van Marrewijk, C.: 2009, *The New Introduction to Geographical Eocnomics*, Cambridge University Press, Cambridge UK.

Bresnahan, T. F.: 2010, General purpose technologies, *in* B. H. Hall and N. Rosenberg (eds), *Handbook of Economics of Innovation*, Vol. 2, Elsevier, pp. 761–791.

Bresnahan, T. F. and Trajtenberg, M.: 1995, General purpose technologies: Engines of growth?, *Journal of Econometrics* **65**, 83–108.

Csikszentmihalyi, M.: 1997, *Creativity, Flow and the Psychology of Discovery and Invention*, Harper Perennial, New York.

Desrochers, P. and Leppälä, S.: 2010, Opening up the 'Jacobs spillovers' black box: Local diversity, creativity and the processes underlying new combinations, *Journal of Economic Geography* pp. 1–21.

Duranton, G. and Puga, D.: 2000, Diversity and specialization in cities: Why, where and when does it matter?, *Urban Studies* **37**(3), 533–555.

Duranton, G. and Puga, D.: 2005, From sectoral to functional urban specialization, *Journal of Urban Economics* **57**(2), 343–370.

Feldman, M. and Audretsch, D.: 1999, Innovation in cities: Science-based diversity, specialization and localized competetion, *European Economic Review* **43**, 409–429.

Feldman, M. P.: 1994, *The Geography of Innovation*, Springer, Boston.

Fritsch, M. and Slavtchev, V.: 2008, Industry specialization, diversity and the effiency of Regional Innovation Systems, *in* C. van Beers, A. Kleinknecht, R. Ortt and R. Verburg (eds), *Determinants of Innovative Behaviour. A Firm's Internal Practices and its External Environment*, Palgrave Macmillan, New York, pp. 272–293.

Garcia-Vega, M.: 2006, Does technological diversification promote innovation? An empirical analysis for European rirms, *Research Policy* **35**, 230–246.

Glaeser, E., Kallal, H., Scheinkman, J. and Shleifer, A.: 1992, Growth in cities, *Journal of Political Economy* **100**(6), 1126–1152.

Graham, S. J. H. and Iacopetta, M.: 2009, Nanotechnology and the emergence of a general purpose technology, *SSRN research paper*.
URL: *http://ssrn.com/abstract=1334376*

Granstrand, O.: 1998, Towards a theory of the technology-based firm, *Research Policy* **25**(5), 467–491.

Handelskammer Hamburg: 2006, Eckpunkte für eine Industriepolitik in Hamburg. Cluster richtig auswählen und entwickeln, Hamburg.
URL: *www.hk24.de/servicemarken/branchen/industrieplatz_hamburg/anlagen/eckpunkte_fuer_eine_industriepolitik_in_Hamburg.pdf*

Henn, S.: 2008, Formierung und Wirkungsgefüge regionaler Technologiecluster: Das Beispiel der Nanotechnologie im Saarland und in Berlin-Brandenburg, *Zeitschrift für Wirtschaftsgeographie* **52**(213), 95–113.

Jacobs, J.: 1969, *The Economy of Cities*, Random House, New York.

Krugman, P.: 1991, Increasing returns and economic geography, *Journal of Political Economy* **99**, 483–499.

Lipsey, R. G., Bekar, C. and Carlaw, K.: 1998, What requires explanation, *in* G. Helpman (ed.), *General Purpose Technologies and Economic Growth*, MIT Press, Cambridge/Ma, pp. 15–54.

Lux Research: 2006, The nanotech report, *Technical report*, Lux Research.

Marshall, A.: 1890, *Principles of Economics*, Macmillan, London.

Maskell, P. and Malmberg, A.: 1999, Localized learning and industrial competitiveness, *Cambridge Journal of Economics* **23**, 167–185.

Mowery, D., Oxley, J. and Silverman, B.: 1998, Technological overlap and interfirm cooperation: Implications for the ressource-based view of the firm, *Research Policy* **27**, 507–523.

National Nanotechnology Initiative: n.d., What is nanotechnology?
URL: *http://www.nano.gov/html/facts/whatIsNano.html*

Paci, R. and Usai, S.: 1999, Externalities, knowledge spillovers and the spatial distribution of innovation, *GeoJournal* **49**, 381–390.

Palmberg, C., Dernis, H. and Miguet, C.: 2009, Nanotechnology: An overview based on indicators and statistics, *STI Working Paper 2009/7*, OECD, Paris.
URL: *www.oecd.org/sti/working-papers*

Palmberg, C. and Nikulainen, T.: 2006, Nanotechnology as a general purpose technology of the 21st century? An overview with focus on Finland, *DIME Working papers Series*.

Porter, M.: 2000, Locations, clusters and company strategy, *in* G. L. Clark, M. P. Feldman and M. S. Gertler (eds), *The Oxford Handbook of Economic Geography*, Oxford University Press, Oxford, pp. 253–274.

Romer, P. M.: 1986, Increasing returns and long-run growth, *Journal of Political Economy* **94**, 1002–1037.

Statistische Ämter des Bundes und der Länder: 2008, *Volkswirtschaftliche Gesamtrechnungen der Länder*.
URL: *http://www.vgrdl.de/Arbeitskreis_VGR/tbls/tab01.asp*

Suzuki, J. and Kodama, F.: 2004, Technological diversity of persistent innovators in Japan. Two case studies of large Japanese firms, *Research Policy* **33**, 531–549.

van der Panne, G. and van Beers, C.: 2006, On the Marshall–Jacobs controversy: It takes two to tango, *Industrial and Corporate Change* **15**(5), 877–890.

Venables, A. J.: 2006, Shifts in economic geography and their ccauses, *Economic Review* **Q**(IV), 61–85.
URL: *http://ideas.repec.org/a/fip/fedker/y2006iqivp61-85nv.91no.4.html*

World Intellectual Property Organization: n.d.
URL: *http://www.wipo.int/ipcpub/#refresh=page*

Wu, W.: 2005, Dynamic cities and creative clusters, *World Bank Policy Research Working Paper* **3509**.

Youtie, J., Iacopetta, M. and Graham, S.: 2008, Assessing the nature of nanotechnology: Can we uncover an emerging general purpose technology?, *Journal of Technology Transfer* **33**, 315–329.

Appendix

A Search terms for publications and patents

We used the Thomson ISI Web of Science, Timespan=1990-2010. The databases were the Science Citation Index - Expanded, Social Sciences Citation Index, Conference Proceedings Citation Index - Science and Conference Proceedings Citation Index - Social Sciences & Humanities, access October/November 2010. The boolean search query was (TS=(Nano* NOT Nano*meter NOT Nano*litre NOT Nano*second* NOT Nano*gram? NOT Nano*molar* NOT Nanobacteri* NOT Nanoheterotroph* NOT Nanophyto* NOT Nanomeli* NOT Nanophtalm* NOT Nanofauna* NOT Nano*aryote? NOT NanoProtist* NOT NanoAlga* NOT NanoFlagel* NOT Plankton) OR TI=(Nano* NOT Nano*meter NOT Nano*litre NOT Nano*second* NOT Nano*gram? NOT Nano*molar* NOT Nanobacteri* NOT Nanoheterotroph* NOT Nanophyto* NOT Nanomeli* NOT Nanophtalm* NOT Nanofauna* NOT Nano*aryote? NOT NanoPro- tist* NOT NanoAlga* NOT NanoFlagel* NOT Plankton)) AND AD=Hamburg). This search resulted in 1315 records.

As we were looking for nano-patents filed in Germany regardless of their value, we used the data-base of the German patent information system (DEPATIS) provided by the German Patent and Trade Mark Office (DPMA), access Oc- tober/November 2010. We used a boolean search strategy; the german search query was (PA=Hamburg ODER IN=Hamburg) UND AC=DE UND PA=DE UND PUB>=01.01.1990 UND (BI=(Nano? NICHT Nano?meter NICHT Nano?liter NICHT Nano?sekunde? NICHT Nano?gram? NICHT Nano?molar? NICHT NatriumNitrat NICHT Nanobak- teri? NICHT Nanobacteri? NICHT Nanoheterotroph? NICHT Nanophyto? NICHT Nanomeli? NICHT Nanophtalm? NICHT Nanofauna? NICHT Nano?aryote? NICHT NanoProtist? NICHT NanoAlga? NICHT NanoFlagel? NICHT Plankton?) ODER TI=(Nano? NICHT Nano?meter NICHT Nano?liter NICHT Nano?sekunde? NICHT Nano?gram? NICHT Nano?molar? NICHT NatriumNitrat NICHT Nanobakteri? NICHT Nanobacteri? NICHT Nanoheterotroph? NICHT Nanophyto? NICHT Nanomeli? NICHT Nanophtalm? NICHT Nanofauna? NICHT Nano?aryote? NICHT NanoPro- tist? NICHT NanoAlga? NICHT NanoFlagel? NICHT Plankton?) ODER AB=(Nano? NICHT Nano?meter NICHT Nano?liter NICHT Nano?sekunde? NICHT Nano?gram? NICHT Nano?molar? NICHT NatriumNitrat NICHT Nanobakteri? NICHT Nanobac- teri? NICHT Nanoheterotroph? NICHT Nanophyto? NICHT Nanomeli? NICHT Nanophtalm? NICHT Nanofauna? NICHT Nano?aryote? NICHT NanoProtist? NICHT NanoAlga? NICHT NanoFlagel? NICHT Plankton?) ODER ICM = B82? ODER ICS = B82?).

B Tables: Decoding IPC classes and subject areas

Code	Thomson ISI Subject Area
BIO1	biochemical research methods
BIO2	biochemistry & molecular biology
CHE1	chemistry, analytical
CHE5	chemistry, multidisciplinary
CHE7	chemistry, physical
CHR	crystallography
ENG3	engineering, chemical
ENG5	engineering, electrical & electronic
ENG12	engineering, multidisciplinary
INS	instruments & instrumentation
MAT2	materials science, ceramics
MAT4	materials science, coatings & films
MAT5	materials science, composites
MAT6	materials science, multidisciplinary
MET1	metallurgy & metallurgical engineering
MUL	multidisciplinary science
NAN	nanoscience & nanotechnology
OPT	optics
PHA	pharmacology & pharmacy
PHY1	physics, applied
PHY2	physics, atomic, molecular & chemical
PHY3	physics, condensed matter
PHY6	physics, multidisciplinary
POL	polymer science
SPE	spectroscopy

Table 4: Coded Thomson ISI Subject Areas (top 25)

Code	IPC Class
A01	agriculture; forestry; animal husbandry; hunting; trapping; fishing
A23	foods or foodstuffs; their treatment, not covered by other classes
A61	medical or veterinary science; hygiene
B01	physical or chemical processes or apparatus in general
B05	spraying or atomizing in general; applying liquids or other fluent materials to surfaces, in general
B23	machine tools; metal-working not otherwise provided for
B29	working of plastics; working of substances in a plastic state in general
B32	layered prodcuts
B64	aircraft, aviation; cosmonautics
B81	micro-structural technology
B82	nano-technology
C01	animal of vegetable oils, fats, fatty substances or waxes; fatty acids therefrom; detergents; candles
C02	treatment of water, waste water, sewage or sludge
C03	glass; mineral or slag wool
C04	cements, concrete; artificial stone; ceramics; refractories
C07	organic chemistry
C08	organic macromolecular compounds; their preparation or chemical working-up; compositions based thereon
C09	dyes; paints; polishes; natural resins; adhesives M compositions not otherwise provided for; applications of materials not otherwise provided for
C11	micro-structural technology
C12	biochemistry; beer; spirits; wine; vinegar; microbiology; enzymology; mutation or genetic engineering
C23	coating metallic material; coating material with metallic material; chemical surface treatment; diffusion treatment of metallic material; coating by vacuum evaporation, by sputtering, by ion implantation or by chemical vapor deposition in general; inhibiting corrosion of metallic material or incrustation in general
G01	measuring; testing
G02	optics
H01	basic electric elements
H02	generation, conversion, or distribution of electric power

Table 5: Coded IPC Classes (top 25)

Working Paper Series in Economics

recent issues

No. 18 *Nina Menz and Ingrid Ott:* On the role of general purpose technologies within the Marshall-Jacobs controversy: the case of nanotechnologies, April 2011

No. 17 *Berno Buechel:* A note on Condorcet consistency and the median voter, April 2011

No. 16 *Eike B. Kroll, Jörg Rieger and Bodo Vogt:* How performance based payoffs influence estimates of complex information? An experimental study on quality and precision in estimation tasks, March 2011

No. 15 *Siegfried K. Berninghaus, Thomas Neumann and Bodo Vogt:* Learning in networks - an experimental study using stationary concepts, February 2011

No. 14 *Marten Hillebrand:* Governmental debt, interest policy, and tax stabilization in a stochastic OLG economy, January 2011

No. 13 *Arne Beck and Matthias Walter:* Tender prices in local bus transport in Germany - an application of alternative regression techniques, December 2010

No. 12 *Eike B. Kroll, Holger Müller and Bodo Vogt:* Experimental evidence of context-dependent preferences in risk-free settings, November 2010

No. 11 *Siegfried Berninghaus, Werner Güth and Stephan Schosser:* Voluntary contributing in a neighborhood public good game - an experimental study, November 2010

No. 10 *Axel Schaffer, Léopold Simar and Jan Rauland:* Decomposing regional efficiency, October 2010

No. 9 *Tobias Lindner:* Das Bundestagswahlrecht aus Perspektive der Social Choice-Theorie, October 2010