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FORMATION AND OUTPUT OF GERMAN NANOTECHNOLOGY COLLABORATIONS: THE ROLE OF PROXIMITY

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Abstract

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Jelcodes:O33,O32

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Abstract

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Keywords:

Proximity, collaboration, nanotechnology, Germany, networks, publication data

JEL code

O33, O32, O38

1. Introduction

Nanotechnology has huge potential in many research areas and opens possibilities in many fields of application (Miyazaki and Islam 2007). The reason for this is that material properties are considerably different on the nanoscale as compared to the same material in bulk or macroscopic form (Miyazaki and Islam 2007). As a consequence

> (n)anotechnology holds the promise of leading to the development of smart nano and micro devices and systems and to radical breakthroughs in vital fields such as healthcare, energy, environment and manufacturing (European Commission 2009, p. 4).

Whether nanotechnology will fully exploit its set of technological, scientific and industrial developments depends on three major questions (Bozeman, et al., 2007): one, how will newcomers and incumbents drive industrial dynamics? Two, how will the knowledge dynamics in nanotechnology, particularly regarding linkages between science and technology? Third, how will institutions, such as network, geographical agglomeration and the job market, support nanotechnology.

The principle idea of nanotechnology emerged more than half a century ago (Feynman 1959) and its first application dates back more than three decades (Binning and Rohrer 1982). Since the early 1990s nanotechnology has emerged from and has connected traditional sciences, such as chemistry, physics, materials science, and biology (Islam and Miyazaki 2009). Ever since, there has been a constant flow of new ideas and application areas from nanotechnology (European Commission 2009). Nanotechnology is one of the key enabling technologies considered as a crucial source of economic growth and employment opportunities (cf. this and the following European Commission 2012a). It affects a vast amount of products in various industrial sectors which include health, food, environment, energy and transport. By 2015 about two million qualified employees will be needed globally in nanotechnology (OECD 2009). So it is no surprise that high on the agenda of policy makers are the appropriate strategies and tools which can support and stimulate the development and deployment of nanotechnology.

Germany has been very successful in worldwide nanotechnology, because it has been one of the world leaders in innovative technologies for the past few decades (c.f. this and the following European Commission 2012b; Forfas 2010; Heinze and Kuhlmann 2008; Jansen et al. 2010). In particular, Germany is the European leader in commercialising nanotechnology. German nanotechnology dates back to the very beginning of its exploration and exploitation, i.e. the early 1990. It has built on its traditionally strong and diverse innovation system. This includes both leading universities and research institutes as well as important engineering, IT and manufacturing industries. These industries are supported by strong and innovative small and medium sized companies. The large and diverse system of publicly funded German research organizations contributes considerably to nanotechnology (cf. this and the following Heinze and Kuhlmann 2008) In particular, the institutes of the Max-Planck Society, the Fraunhofer Society, the Leibnitz Association and the Helmholtz Research Centers have been carrying out research in nanotechnology. These research organizations have developed a particular profile. Although the institutes of the Max-Planck Society focus on fundamental research, those of the Fraunhofer Society concentrate instead on applied contract research. In contrast, the Helmholtz Research Centres manage big-science research facilities. As a consequence, there has been little collaboration between these non-university organizations. At the same time they collaborate on a regular basis with universities and firms. The institutes of the Leibnitz Association are an exception, and have a diverse and undifferentiated profile.

Knowledge networks (Brenner et al. 2011), collaborations and proximity (Cramton 2001; Cunningham and Werker 2012; Lavie and Drori 2012; Pandza et al. 2011) have been thoroughly investigated in the past. In particular, proximity between collaboration partners has been of the essence in the creation, transfer and use of knowledge. Proximity of different kinds influence the success of collaborations as it proximity either facilitates or hampers collaboration output. Different forms of proximity can also play a role. On top of geographical proximity, organizational, cognitive, technological, social, systemic or personal proximity all potentially influence collaboration output (e.g. Boschma 2005; Caniëls et al. forthcoming; Cunningham and Werker 2012; Knoben and Oerlemans 2006; Morgan 2004). Such findings have been confirmed in data. For European nanotechnology, Cunningham and Werker (Cunningham and Werker 2012) show the influence of organizational, geographical and technological proximity on collaboration success. Geographical proximity has a significant effect on collaboration output. Technological proximity makes collaborations more productive if the partners are sufficiently different from each other so as to benefit from a wider range of knowledge while being at the same time sufficiently similar so as to understand each other. However, organizational proximity influences the output of collaborations in European nanotechnology only indirectly via technological proximity. Academic organizations are more successful in brokering relationships across a wide range of potential topics compared to non-academic organizations. The latter are more productive at the expense of being more specialized in their technological and collaborative interactions. Moreover, Autant-Bernard et al. (2007) show the influence of social network effects and geographical proximity on nanotechnology output for European nanotechnology. For the U.S. Shapira and Youtie (2008) present regionally tied ”nanodistricts” in the form of government dominated districts, university dominated districts, and high technology districts which combine strong regional ties with global ties.

In this paper, we will concentrate on the influence of organizational, technological, physical and systemic proximity on both the formation and the output of collaboration in German nanotechnology. Thereby, we add to the existing insights into the relationships between proximity and collaborations in two ways. One, to our knowledge for the first time, we distinguish the formation of collaborations from their output. This gives us the opportunity of providing a more nuanced picture of the influence different kinds of proximity can have on the evolution of collaborations. Two, we do not only investigate the influence of geographical, organizational and technological proximity on collaborations but we open the black box of geographical proximity. We open the black box by distinguishing physical from systemic proximity. Thereby we are able to disentangle the role of pure physical distance (for instance in terms of commuting time) from the effects of the innovation system.

The paper is organized as follows. Based on theoretical considerations regarding knowledge, proximity and collaboration we build a conceptual model and hypotheses (Section 2). Accordingly, we model the relationships between proximity and collaboration and construct indicators representing the dependent and independent variables employed (Section 3). In Section 4 we provide detailed insights about the relationship between proximity and collaboration for German nanotechnology and derive implications for management and policy. Finally, we round our paper with a short summary of our results and some indications of further research questions (Section 5).

2. Proximity and Collaboration in Nanotechnology: Conceptualization and Hypotheses

To thoroughly investigate the role of proximity for collaboration we introduce a conceptual model based on previous research (Section 2.1). Then we introduce dependent variables on formation and output (Section 2.2), as well as independent variables on proximity (Section 2.3). These variables will be used later in a full, empirical model of collaboration and proximity.

2.1 Proximity and Collaboration in Nanotechnology: A Conceptual Model

Collaborations and the resulting networks are vital for the exploration and exploitation of nanotechnology because of its three following characteristics: one, nanotechnology's interdisciplinary character; two, its still rather early stage of development; and three, its spread throughout the world (c.f. this and the following Salerno et al. 2008). As our surroundings consists of molecules and atoms there is no difference between titanium particles or proteins when operating at the nano-level. For that reason, nanotechnology unites several fundamental disciplines being able to solve problems at the resolution of one billionth of a meter. Nanotechnology is still in its early stage. Nonetheless it has considerable growth potential for the coming decades (Roco et al. 2011). Because of its interdisciplinary character and its early stage of development nanotechnology has the potential to expand widely and rapidly in the future. Moreover nanotechnology drives breakthroughs all over the world in various markets and industries (Roco et al. 2011). As a consequence, single scholars and often even single organizations are not able handling innovation and technological change in nanotechnology on their own.

The creation, transfer and use of knowledge and innovation is crucial for the development and deployment of key enabling technologies, such as nanotechnology. Innovation and technological development benefit from complementary skills of individuals, universities, firms, public policy agents and others (Pandza et al. 2011). As the knowledge necessary for nanotechnology is too complex to be dealt with by individual scholars, scholars have to form collaborations supporting the creation, storage and transfer of knowledge and innovation (Salerno et al. 2008). Often collaborations connect individual scholars far beyond their own teams and organizations. Consequently, innovation and technological change in nanotechnology emerge from efforts of scholarly networks rather than from individual efforts (Powell et al. 1996). Its potential can be only realized in world-wide international and inter-organizational collaboration networks (Pandza et al. 2011). For scholars working in the field of nanotechnology their ability of effectively communicating with colleagues and of understanding and relying on a broad spectrum of disciplines proves to be crucial for creating new ideas (Heinze and Bauer 2007). In order to be successful, scholars in nanotechnology must have access to and use knowledge from a broad spectrum of disciplines. As knowledge transfer within collaborations often increases creativity and fosters new ideas in nanotechnology scholars benefit from forming collaborations. In particular, those scholars whose networks are more open for new connections show higher citation scores and higher scientific output (Heinze and Bauer 2007; Islam and Miyazaki 2009). In the following, we consider scholars' external collaborations with scholars from other organizations, regions and countries.

The formation and output of nanotechnology collaborations depends on the quality and quantity of the underlying processes of knowledge transfer and creation. As we will show knowledge transfer and creation may be either enhanced or hampered by proximity of different kinds. In the following, we look into the influence of technological, organizational, physical and systemic proximity.

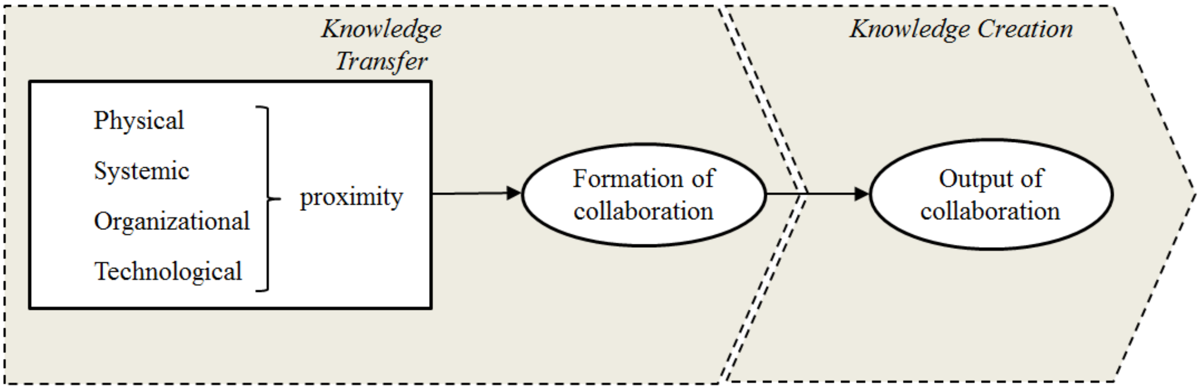

Figure 1: Proximity and Collaboration: A Conceptual Model

As shown in Figure 1 proximity is crucial for knowledge transfer and creation enabling and stimulating the formation and output of collaborations. The transfer of knowledge takes place during the formation of collaborations and the production of their output. While collaborating the partners also create new knowledge. In Figure 1 we represent the complex knowledge processes underlying the formation and output of nanotechnology collaborations in a simplified way. The conceptualization as shown in Figure 1 serves as a starting point for modelling collaboration and proximity in Section 3. Before that we will elaborate on each of the facets concepts of collaboration (Section 2.2). We also elaborate on each of the forms of proximity as well as the expected impacts on collaboration (Section 2.3).

2.2 Formation and Output of Research Collaborations: The Dependent Variables

Collaboration is the "working together of researchers to achieve the common goal of producing new scientific knowledge" (Katz and Martin 1997, p. 7). The concept of collaboration is complex and multidimensional for at least two reasons: One, to define who is a collaborator and to measure the exact contribution of every scholar to the final output is very difficult. In fact, research collaboration is ill-defined and who is an acknowledged partner contributing to the output of collaborations is a matter of social convention and open to negotiation (Katz and Martin 1997). Two, collaborations take place over a longer period of time. Time is required in getting to know potential partners, starting the collaboration, actually working together, producing output in terms of publications or patents, and in developing joint research through Ph.D.s or master students. Eventually either the collaboration stops or it is necessary to redesign the collaboration after the original project terminates. As a consequence, what affects collaborations at one stage might not have an influence on them at another stage.

In the following we distinguish two stages in the collaboration process, i.e. forming the collaboration and producing output (see also Section 2.1 and Figure 1). Potential partners must put effort into a collaboration by looking for the adequate partner and by starting to build trust that is necessary for the complex and inherently uncertain endeavour ahead. When collaborating partners need to transfer their relevant knowledge, use individual and joint knowledge and create new one as a result. At the same time, collaborations might not lead to output and might be unstable. So, an initial joint research project might in fact also be the last. Such failed collaborations may occur because of a personal mismatch, a too large technological, organizational, physical or systemic distance, or a fundamental discontent about the way of working together or the results achieved (Caniëls et al. forthcoming). Moreover, random meetings may result in a productive one-at-a-time project while long-standing collaborations might lead to collaboration lock-ins because partners are staying on one research path, unable to think out of the box again which might hamper creativity.

2.3 Different Kinds of Proximity: The Independent Variables and The Hypotheses

To build the hypotheses we suggest that the formation of collaborations might require other kinds of proximity than their maintenance and development eventually leading to output. Therefore, we consider the following two stages when analysing collaboration: In the first stage partners form the collaboration; in the second stage they produce research output (see also Section 2.2). We suggest that technological, organizational, physical and systemic proximity may differently affect the formation of collaborations and their productive output (see Section 2.3).

Cognitive proximity between agents exist when their knowledge bases partly overlap (Boschma 2005; Nooteboom et al. 2007). It encompasses technological proximity where agents rely on shared technological experiences (Cunningham and Werker 2012; Knoben and Oerlemans 2006). For the following reasons an inverted U-shaped relationship is suggested between technological proximity on the one hand side and collaboration output on the other hand side (cf. this and the following Colombo 2003). Agents need to be sufficiently similar in their technological knowledge bases in order to understand each other. At the same time they need to be different enough to learn from each other. When agents are very different in their knowledge bases there is a lot be learned but also learning is more difficult. Former empirical investigations show that the relationship between technological proximity and collaboration shows the U-shaped pattern suggested (Cunningham and Werker 2012; Nooteboom et al. 2007) The positive impact of collaboration partners being technologically close peaks at a certain level after which it drops. As knowledge is widely dispersed amongst the scholars in the nanotechnology network and diverse due to the interdisciplinary character of nanotechnology partial overlap of technological experiences is crucial for successfully collaborating in nanotechnology.

Thus, drawing on the results of former analyses we expect a U-shaped relationship between technological proximity on the one hand side and the formation and output of collaboration. While this relationship has been earlier established between technological proximity and collaborative output, here – to our knowledge – for the first time we investigate this relationship for technological proximity and the formation of collaborations. The higher the opportunities to successfully collaborate, the more inclined potential partners are to embark on a joint research endeavour. In existing collaborations the right degree of technological proximity makes the relationship even more productive. Accordingly, we formulate the two following hypotheses:

H1: The likelihood of potential partners to form a collaboration is highest when they are technologically close but not too close.

H2: The output of collaborations is highest when partners are technologically close but not too close.

Organizational proximity means that partners are close with respect to the structure and the related incentives of their organization (Boschma 2005; Broekel and Boschma 2012; Caniëls et al. forthcoming). Here, we suggest that collaborations between the same kind of organization may be easier than between different types of organizations (cf. this and the following Lavie and Drori 2012; Heinze and Kuhlmann 2008). Universities share costs of their research literature or equipment and facilities by collaborating. Moreover, they have other incentives regarding output, namely publishing, and visibility. This is often in in contrast with the incentives of firms which might be either interested in patenting research results or keeping them secret in order to have a competitive advantage.

While organizational proximity might help collaborating successfully (Boschma 2005), being too close might lead to lock-ins. In line with Cunningham and Werker (2012) we ignore the possibility for lock-ins in the following analysis: As we analyse collaborations with the help of publication data it is very unlikely to be confronted with lock-ins. The reason for this is that authors have to build their argument on former research of others and are controlled by reviewers when publishing in the peer-reviewed journals that we use as our data here. Accordingly, we formulate the following two hypotheses:

H3: Organizational proximity of potential partners positively influences the formation of collaborations.

H4: Organizational proximity of partners positively influences the collaborative output.

In the following we open the black-box of geographical proximity dating back to the seminal work of Alfred Marshall on industrial districts that has since been thoroughly investigated (Marshall 1920; Belussi and Caldari 2008). We suggest that geographical proximity contains two aspects masked by using the overall concept of geographical proximity. Therefore, we distinguish pure physical proximity from systemic proximity (for a first attempt of empirically distinguishing pure physical and systemic distance see Cunningham and Werker 2012). The concept of pure physical proximity describes the effects stemming from collaboration partners being close in terms of physical distance (e.g. measured in km) or the time partners need to travel to each other (e.g. commuting time by car or public transport). Despite the fact that in the last decades in our global digitalized world with e-mail messages and Skype physical proximity have seemingly become less important face-to-face contacts between scholars still seem to enable research (Morgan 2004).

Theoretical and empirical investigations suggest that physical proximity positively affects the output of research collaborations (Broekel and Boschma 2012; Cunningham and Werker 2012; Knoben and Oerlemans 2006; Katz and Martin 1997). More generally spoken, physical proximity also positively influence the diffusion of knowledge in the network (Rivkin and et.al. 2006). This might eventually lead to innovation and technological progress which is particularly important for a multidisciplinary field such as nanotechnology. We suggest that physical proximity positively affect both the formation and the output of collaborations:

H5: Physical proximity of potential partners positively influence the formation of collaborations.

H6: Physical proximity of partners positively influence the output of collaborations.

Systemic proximity accounts for the effects of geographical proximity that are not due to pure physical closeness, i.e. the effects emerging because (potential) partners are located in the same regional innovation system. As regional and national innovation systems have been shaped by different political, economic, and cultural influences being part of the same or neighbouring regional innovation systems might enable joint research projects because of similar formal and informal institutions (e.g. laws, codes of conducts, routines and habits), language and culture (cf. this and the following Fromhold-Eisebith and Werker 2013; Asheim et al. 2011; Cooke and et al. 1997). Moreover, universities, firms and other research organizations are subject to the same policy measures and incentives. As a consequence, scholars within the same or neighbouring regional innovation systems share, transfer and create knowledge more easily. Too much systemic closeness might lead to negative lock-ins, as collaboration partners lack sufficient input from outside the regional innovation system. Nonetheless we suggest that, in line with our reasoning regarding organizational proximity, the effect is marginal here. We analyse co-publication in peer-reviewed journals, and self-plagiarism is adjudicated by reviewers. As a consequence we suggest that (potential) partners increase the chance of forming a collaboration as well as of being more productive in an existing collaboration when being systemically close:

H7: Systemic proximity of potential partners positively influence the formation of collaborations.

H8: Systemic proximity of partners positively influence the output of collaborations.

3. Proximity and Collaboration in German Nanotechnology: Data, Indicators and Regression Models

In order to test the hypotheses developed in Section 2.3 we run regression analyses using indicators based on bibliometric and geographical data as well as the NUTS classification system. We start by building the German nanotechnology network from publication data (Section 3.1). After that, we present the independent variables, i.e. variables on proximity as well as interaction and control variables (Section 3.2). Finally, we introduce construct the two regression models by combining the independent variables with the dependent variables representing the formation and the output of German nanotechnology collaborations (Section 3.3).

3.1 Building the German Nanotechnology Network From Publication Data

From publication data we constructed the German nanotechnology network. In particular, we analysed co-authorship based on publication data. This method allows us to analyse a large sample and provides us with statistically significant results (Katz and Martin 1997). We used the Web of Science database of Thomson Reuters (2012). This database contains – amongst others -- abstracts, keywords, the names of authors and their affiliations. We used the query by Arora et al. (2013) specifically designed to capture the latest achievements in nanotechnology. Carrying out this query for the time period of three years, i.e. from 2010 to 2012, left us with more than 270,000 publications in the Web of Knowledge. We included all publications with at least one author affiliated to a German organization, i.e. about 20,000 publications produced by more than 2,000 organizations. Based on these publications we built a network of inter-organizational collaboration using co-authorship, i.e. if two authors from different organizations were listed on a publication we considered this a collaboration between these authors and their affiliations. We limit our analysis to inter-organizational collaborations only, i.e. we did not include publications written by co-authors affiliated with only one organization. The resulting German nanotechnology networks is highly sparse with a long tail of organizations only rarely contributing to nanotechnology. Hence, we focus on the most productive organizations, thereby following a well-established procedure in publication analysis (Lotka 1926).

In the following, we restrict our analysis to the one hundred German organizations most productive in nanotechnology (see also Cunningham and Werker 2012). To identify the one hundred most productive German nanotechnology organizations we prepared the data in two steps: One, we disambiguated the names of the organizations in the database as organizations use variations of their names including English and foreign versions of it. Two, we allot research output by equally crediting each author on the paper. Then, we add up all the credits for all existing collaborations between organizations (for a similar scheme of fractionating co-patenting see Maggioni et al. 2007). Here, we are only interested in the collaborations actually materializing between research organizations. By this scheme we identify the one hundred German organizations most productive in nanotechnology research. The nanotechnology publications of the top one hundred German organizations account for more than 90% of the nanotechnology publications provided by German organizations in this period (and more than 24% of world nanotechnology publications). Therefore, we can give a thorough if not thoroughly complete picture of the network within which German nanotechnology.

The German nanotechnology network is illustrated in Figure 2. In order to show the importance of organizations within this network we calculated the eigenvector centrality (Hannemann and Riddle 2005). The eigenvector centrality helps us identifying the most central organizations within the global structure of the overall German nanotechnology network. The size of the nodes indicate the level of the eigenvector centrality, i.e. the higher the eigenvector centrality is the bigger the node is The thickness of the links between organizations mirrors the amount of joint publications, i.e. the thicker the line the more output a joint collaboration organizations produces. Again we fractionate publications to account for the contribution of authors and organizations (see Section 3.1 for details).

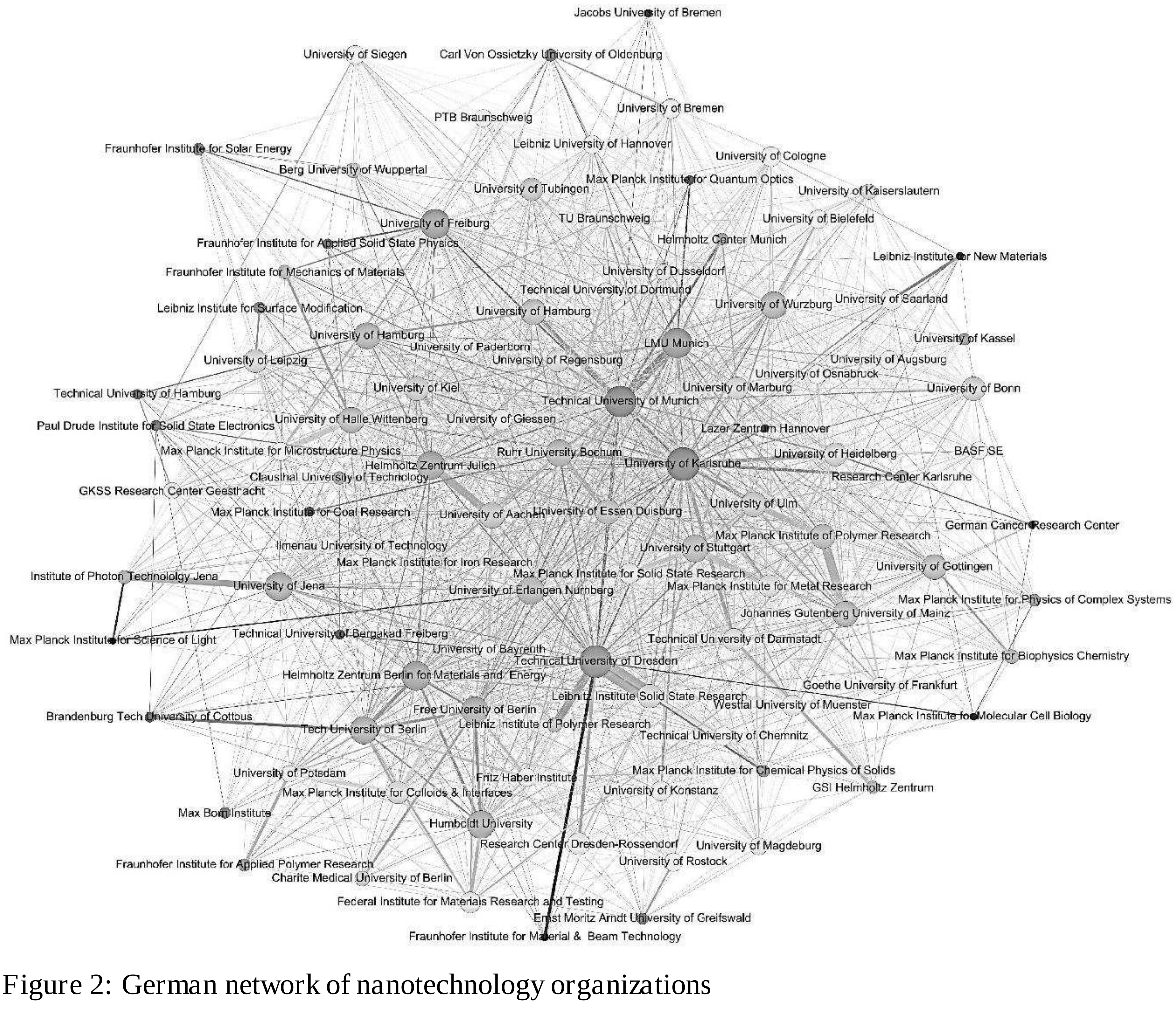

Figure 2: German network of nanotechnology organizations

The German network of nanotechnology organizations looks like follows: It mainly consists of universities and public-funded research organizations, such as Max-Planck Society, of the Fraunhofer Society and of the Leibniz Association as well as the Helmholtz Research Centres. Only one firm, BASF, appeared in our analysis. This is not surprising as with publications we primarily depict the academic nanotechnology network. As a rule firms do not aim at publishing their results in academic journals (Nelson et al. 2014). In our analysis period of 2010 until 2012 38.2% of inter-organizational collaborations took place between universities, 14.2% between 'non-universities' organizations, as well as 47.6% between universities on the one hand side and non-universities on the other hand side. Among the top ten organizations accounting for a quarter of German nanotechnology publications we find three publicly funded research organizations. It is notable that there is a representative of every major research association with the exception of the Fraunhofer Society which ranks on the 84^{th} place here. This is not surprising as the focus of their research lies on applied research which does not lead to publications in the first place but to patents, innovation etc. (Nelson 2009). A striking feature of the German innovation system in general and of the nanotechnology system in particular is large share of publicly funded research outside the universities and in the research associations (Heinze and Kuhlmann 2008).

3.2 Independent Variables: Data and Indicators

The independent variables comprise those representing technological, organizational, physical and systemic proximity as well as a control variable and a number of interaction variables. For building the indicators representing the independent variables we used publication data, the NUTS classification system and geographical information from Google Earth.

The variables representing technological proximity rely on publication data. In order to measure technological proximity we constructed a research profile for each of one hundred leading German organizations as well as for the 4,950 possible collaborations amongst them. We constructed the research profiles by using the science categories of Web of Science. The query used here provided us with six main categories for nanotechnology (Arora et al. 2013) to which we added an "everything else" category capturing the non-nanotechnology publications (for an overview of the categories please refer to Appendix A). In order to identify the research profile of the one hundred leading German organizations we calculated the share of publications of an organization falling into these seven categories (cf. a similar approach Cunningham and Werker 2012). We did this by including all papers published by an organization, fractionally weighted by that organization's contribution. (For the method of fractionation see also Section 3.1). In order to identify technological closeness between collaborators we calculated the research profiles for each of the 4,950 possible collaborations between the one hundred leading German organizations. These were based on the separate and joint publications falling in each of seven subject categories, as mentioned above. By comparing the individual technological profile of an organization to the collaborative profile we can identify the degree of technological proximity. Technological proximity is calculated as follows:

$$INFO(x, y) = \sum_{i \in X} \sum_{j \in Y} p(x_i, y_j) \log(\frac{p(x_i, y_j)}{p(x_i)p(y_j)}) \quad (3)$$

With INFO (x, y) we combine both relational information, i.e. the collaborative output as well as non-relational information, i.e. the typical output of each of the partners. This formula is well-known and builds on the mathematical theory of communication (Shannon 1948) which has been widely discussed in information theory (MacKay 2003). When calculating the joint profiles of organization x and y we consider each subject category i (see Appendix A). We include both the profile of research done individually, p(x) and p(y), as well as the one done jointly, p(x,y). If organizations share exactly the same profile, technological distance between them is zero. While in principle the distance could climb to infinity, here we ensure some minimum amount of technological proximity because of the category of 'everything else.'. In the following, we use the unit of technological proximity in terms of quantities information. The correct unit for information using log(10) units is known as the Hartley; these can be easily converted to the more familiar bit of computer science, which is measured in log(2) units.

Organizational proximity is based on publication data. Two dummy variables represent organizational proximity. These variables in combination are aimed to show if organizational proximity influences the formation or output of collaborations. We included one dummy variable indicating whether both of the collaborators are universities (University) and another one indicating whether both of them are 'non-universities' (Non-University). These two dummy variables represent three possible kinds of collaboration: one, only university partners collaborating (1 for the dummy University and 0 for the dummy Non-University), two only non-universities collaborating (0 for the dummy University and 1 for the dummy Non-University), and three a mix of both organizational types (0 for both dummies). As the dummies only score in cases of pure academic or non-academic collaborations the mixed case is our reference. We also look into the interaction between organizational type and technological proximity with the help of the terms Technological distance * University and Technological distance * Non-University (@Scott, perhaps you can find better ways to express this). Non-university organization does not only mean researchers from firms, but in particular also contains the institutes of the Max-Planck Society, of the Fraunhofer Society and of the Leibnitz Association as well as the Helmholtz Research Centers (for more details see introduction).

Physical proximity is the part of geographical proximity stemming from pure bodily closeness between collaborators (for details see Section 2.3). The geographical information we obtained by collecting the latitude and longitude data of the affiliation addresses given (for more information see Appendix A). The data stems from Google Maps (Google, 2013) and contains a ratio scaled variable which is the logarithm of the distance between collaborating organizations. The formula used for the calculation of the physical distance is as follows:

$$D = \arccos[\sin\left(\frac{Lat1}{180^o} * \pi\right) * \sin\left(\frac{Lat2}{180^o} * \pi\right) + \cos\left(\frac{Lat1}{180^o} * \pi\right) * \cos\left(\frac{Lat1}{180^o} * \pi\right) * \cos\left(\frac{Lon1}{180^o} * \pi - \frac{Lon2}{180^o} * \pi\right) * R]$$

with D as distance, Lat and Lon as latitude and longitude data of pairs of collaborators and R as radius of the earth. This is simply the mathematical formulation of the Great Circle distance between two points on a sphere.

Systemic proximity is the part of geographical proximity mirroring that collaborators belong to the same or neighbouring innovation systems (for details see Section 2.3). We use the Nomenclature of Territorial Units for Statistics (NUTS) classifications system to mirror systemic proximity. This classification is a hierarchical system for dividing up the economic territory of the European Union using the three levels NUTS 1, NUTS 2, and NUTS 3 (Eurostat 2011). NUTS 1 relates to major socio-economic regions, i.e. the German Länder, NUTS 2 to more disaggregated units often used for implementing specific regional measures, i.e. mostly the German (former) Regierungsbezirke and NUTS 3 to small regions that are used for specific diagnosis, i.e. the German (Land)kreise and kreisfreie Städte (European Commission, 2014).

In addition to the independent variables representing the technological, organizational, physical and systemic proximity we add a control variable and a number of interaction terms. We include the total number of publications of a pair of organizations as a control variable in the regression models. The purpose of the variable is to control for the output of organizations. On top of the control variable we include three interaction variables. As first interaction variable we take the square of technological proximity. This variable controls for the possible non-linear effect expected for technological proximity (see Section 2.3). For the two other interaction variables we multiply organizational by technological proximity. These interaction variables account for how universities as well as other organizations mediate technological proximity.

In Table 1 you find all independent variables and their descriptions.

Variable	**Name**	**Description**
Technological proximity		
X_1	Technological distance INFO(x,y)	Overlap of research specialisations of collaborators: 0 means complete overlap and 1 none at all
Organizational proximity		
X_2	University (Univ)	Both of the collaborators are affiliated with a university
X_3	Non-University (NUniv)	Both of the collaborators are not affiliated with a university
Physical distance		
X_4	Physical distance	Logarithm of km distance between collaborators
Systemic proximity		
X_5	Shared NUTS1	Shared NUTS1 region
X_6	Shared NUTS2	Shared NUTS2 region
X_7	Shared NUTS3	Shared NUTS3 region
X_8	Bordered1	Bordering NUTS1 regions
X_9	Bordered2	Bordering NUTS2 regions
X_{10}	Bordered3	Bordering NUTS3 regions
Control variable		
X_{11}	Publication	The average of the logarithm of the total number of publications
Interaction variables		
X_{12}	Square of Technological distance	Square of Technological Distance
X_{13}	Technological distance * University	Interaction of University and Technological Distance
X_{14}	Technological distance * Non-University	Interaction of Non-University and Technological Distance

Table 1 – *Regression models' variables*

3.3 Dependent Variables and The Regression Models

In order to account for the two stages of collaboration investigated here (see also Figure 1 in Section 2.1) we define two different dependent variables, i.e. the formation and the output of collaboration. Accordingly, we apply two different regression models capturing the influence of proximity on the formation (model A) and the output (model B) of collaboration in German nanotechnology. The independent variables (see Section 3.2) are the same for models A and B.

In the first model (model A) the dependent variable is the likelihood of two organizations in the network actually collaborating. Model A specifically tests the influence of different kinds of proximity on the formation of collaborations, i.e. it tests hypotheses 1, 3, 5, and 7. Model A is a binary logistic regression capturing the influence of independent variables on a dependent dichotomous variable. Particularly in our model A we show the likelihood of organizations forming a link with another one governed by technological, organizational, physical and systemic proximity. Accordingly, the equation of model A is specified as follows

$$Y(X_1,...,X_n) = \frac{e^{(\alpha+\beta_1 X_1+...+\beta_n X_n)}}{e^{(\alpha+\beta_1 X_1+...+\beta_n X_n)}+1} \quad (1)$$

with Y being the binary dependent variable, α the intercept, β the coefficient for independent variable and X_i being the independent variables. The dependent variable is binary indicating either the existence or the absence of a link between two organizations. If the number of publications between two organizations is zero the variable is also zero indicating the absence of collaboration links between the two organizations. If there is at least one publication with authors affiliated to both organizations the variable scores 1, indicating the existence of a collaboration between the two collaborations. We take all 4,950 potential links between the one hundred German organizations most productive in nanotechnology into account here.

The second model (model B) specifically tests the influence of different kinds of proximity on the output of existing collaborations. Output, in terms of total publications, is the dependent variable in model B. This means that model B tests hypotheses 2, 4, 6, and 8. Model B, a negative binomial regression, is specified as follows

$$Y(X_1,...,X_n) = \alpha + \beta_1 X_1 + ... + \beta_n X_n \quad (2)$$

with Y being the dependent variable, α an intercept, β the coefficient of independent variable and X_i the independent variables. The dependent variable is ratio scaled. It was calculated by adding up the fractionated publications of each collaboration (for the method of fractionation see Section 3.1). In total we found 1,994 collaborations in the German nanotechnology network constructed here.

4. Proximity and Collaboration in German Nanotechnology: The Outcomes

In the following we discuss the outcomes of our analysis on proximity and collaboration in German nanotechnology. We start with giving an overview of the results of our regression analyses (Section 4.1). Then, we interpret technological and organizational proximity as drivers of German nanotechnology collaborations in terms of its formation and its output (Section 4.2). After that we discuss the role of geographical proximity which is split up in physical and systemic proximity, thereby opening the black box of geographical proximity (Section 4.3).

4.1 Proximity and Collaboration in German Nanotechnology: An Overview of the Results

We use two different model specifications, therefore we need two distinct approaches to generalize and interpret the parameters. Model A is explaining the formation of collaboration. For model A we provide the beta coefficients with the corresponding odds ratios, i.e. Exp (B), as the coefficients alone just show the power of an exponent in the regression model and are hard to interpret. Model B explains the output of collaboration. For Model B we provide the B both unstandardized and standardized. In Table 2 you find an overview of all variables' coefficients, their significance and their standard errors.

	Model A: **Formation of Collaboration** Logistic regression		Model B: **Output of Collaboration** Multi-linear regression	
	Hypotheses: 1, 3, 5, 7		Hypotheses: 2, 4, 6, 8	
Independent variables	B	Exp(B) Odds ratio	B Unstandardized	Beta Standardized
Technological Proximity				
technological distance	2.777* (.234)	16.076	.831* (.079)	.264
Organizational Proximity				
University (Univ)	3.172* (.375)	23.857	-.074 (.060)	-.035
Non-University (NUniv)	-1.120* (.240)	.326	-.313** (.105)	-.082
Physical Proximity				
Physical distance	-.231* (.120)	.794	-.042 (.040)	-.041
Systemic Proximity				
Shared NUTS1	.341 (.333)	1.407	-.013 (.106)	-.004
Shared NUTS2	.853 (.653)	2.347	.168 (.194)	.036
Shared NUTS3	-.176 (.709)	.838	.639** (.207)	.113
Bordered NUTS1	.282 (.157)	1.326	-.022 (.052)	-.010
Bordered NUTS2	.091 (.279)	1.095	.287** (.089)	.087
Bordered NUTS3	-.342 (.568)	.710	.041 (.186)	.005
Control Variable				
Publication	2.369* (.131)	10.685	.430* (.044)	.197
Interaction Variables				
Square of technological distance	-10.197* (.471)	.000	.717* (.153)	.139
Technological distance * Univ	-6.549* (.746)	.001	.602** (.210)	.095
Technological distance *NUniv	2.258* (.583)	9.567	.000 (.319)	.000
Constant	2.608* (.147)	13.569	-.404* (.048)	-

Table 2: Regression models' coefficient
(* the level of significance of the coefficient at 0.01 and ** at 0.05)

The analysis of the control variable, i.e. publication, shows three important results. One, the more publications an organization produces the more often it will seek out collaborate (model A). Second the more the partner organizations produce, the higher the expected output of any given collaboration, all things considered (model B). This effect is expected, because the more an organization publishes the higher its academic success and reputation is. This means that the more it publishes the more desirable it is for future collaborations. Furthermore, a positive association between prior publication and publication output in collaboration would be expected only by chance. As this effect was expected we controlled for it in order to avoid that it is captured by any other variable. The resultant model shows the incremental publication above expected output for any collaboration pair. A third finding is that German publications on nanotechnology are mainly the result of collaborative research. This is reflected in the high odds ratio for the publication variable in Model A.. If it would be done mainly internally the odds ratio for this variable would be much smaller. Three, organizations not only look for new research partners but actively involve smaller parties to participate in existing collaborations. Prior institutional publication is introduced as a control variable in this model. If collaboration is in proportion to existing publication the coefficient is 0.50. Here the publication coefficient is less than 0.50, indicating the network is disassortative – large publishers actively seek and incorporate less active publishing organizations into the network.

4.2 Proximity Driving Collaborations in German Nanotechnology

Generally spoken, for German nanotechnology our results provide a more nuanced picture of the relationships between proximity and collaboration. First of all, the distinction between the formation and output of collaboration as dependent variables discloses that technological, organizational, pure physical and systemic proximity affects the stages of collaborations in different ways. Second, the distinction between pure physical and systemic proximity opens the black box of geographical proximity.

Regarding technological proximity we confirm former findings on its relationship with collaboration, with one nuance though. In line with former findings on technological proximity and its effect on output of collaboration in particular (Broekel and Boschma 2012; Cunningham and Werker 2012; Ter Wal 2013) we show that partners start a collaboration most likely when they are close but not too close in terms of technological profile. Thus, we do not reject hypothesis 1. When looking at the collaborative output though, we see that for existing collaborations technological distance goes hand in hand with an increase in output as the output variable the square of technological distance has a positive sign. It is a rather small effect but significant. Thus, we partly reject hypothesis 2. In particular, we show that the U-shaped relationship exists only between technological distance and the formation of a collaboration not between technological distance and eventual output. This indicates that too large a technological distance affects a collaboration already in the formation phase, i.e. the partners do not embark on joint research project. In cases partners embark joint research projects they are particularly fruitful the more different they are in technological terms.

Our findings on organizational proximity point to the fact that the organizational set-up of German nanotechnology is very specific (see also Sections 1 and 2.3). Organizational proximity shows clear effects on the formation of collaborations and some effects on the output. Collaborations containing both academic and non-academic partners are our reference point to which we compare the collaborations containing only academic partners and the ones containing only non-academic partners. According to hypotheses 3 and 4 these mixed collaborations serving as our reference point would do worse compared to the collaborations either containing only academic or only non-academic partners. However, we have to partly reject hypothesis 3: forming a collaboration is easiest with only academic partners which is in line with hypothesis 3. However, it is most difficult with only non-university partners which is not in line with hypothesis 3. Moreover, we have to reject hypothesis 4 completely, as interestingly mixed collaborations produce the highest collaborative output. We suggest that this result reflects the specific set-up of the German innovation system: While German universities usually span a broad spectrum of disciplines relevant for nanotechnology research the publicly funded non-university sector is extremely specialised with some organizations focusing on basic and some on applied research (BMBF 2012) In particular, organizations from the large publicly funded non-university sector were organized according to specializations, e.g., the institutes of the Max Planck Society have traditionally focused on basic research while the institutes of the Fraunhofer Society have concentrated on applied research (BMBF 2012). As the non-university organizations differ so substantially in the purpose of their research it is not surprising that it is most difficult for them to form a collaboration. So, our results confirm that organizations from the publicly funded non-university sector have not traditionally collaborated with each other (Heinze and Kuhlmann 2008).

Looking at the interaction terms between technological and organizational proximity we see the particular situation of the German non-academic sector reflected as well. When the technological distance increases the formation of a collaboration becomes more unlikely between academic partners and more likely between non-academic partners - again compared to mixed collaborations between academic and non-academic organizations. As the organizations of the German non-academic sector of publicly funded organizations are so profoundly specialized they are often from the very outset technologically distant. Interestingly, if collaborations between academic partners exist their output is the higher the more technologically distant they are.

By distinguishing physical from systemic proximity we open the black box of geographical proximity providing nuanced results. Our outcomes reveal that while physical proximity affects the formation of collaborations systemic proximity partly affects the output of collaborations. Physical proximity influences the two stages of collaboration, i.e. formation and output of collaboration differently. Our findings show that physical proximity goes hand in hand with the formation of collaborations, thereby supporting hypothesis 5. In contrast, physical proximity does not influence collaborative output, so that we reject hypothesis 6. The outcomes obtained for the systemic proximity show that it has no influence on the formation of collaborations. However, belonging to the same NUTS3 region or being located in bordering NUTS2 regions positively affects collaborative output. So, we reject hypothesis 7 and do not reject hypothesis 8. The positive influence of belonging to the same NUTS3 region indicates that local links with the possibility of face to face contact are important for collaborative output. This is in line with former analyses indicating that on local levels organizations successfully form small regional innovation systems using established links, thereby exploiting the benefits of sharing common knowledge and institutions (Cooke et.al. 1997).

That collaborative output is positively affected by partners being located in bordering NUTS2 regions cannot be explained straightforwardly. A possible explanation is that German NUTS1 level policy (Länder policy) tries to fairly distribute research functions in space so that the research organizations are distributed amongst the its few neighbouring NUTS2 level regions. When policy stimulates connections between this geographically distributed organizations this would show an effect on the neighbouring NUTS2 regions. This would also explain why belonging to the same NUTS1 regions does not seem to have any influence on collaborative output. It would be already captured by the bordering NUTS2 regions.

4.3 Suggestions for University Management and Research Policy

Our results indicate a number of promising routes for university management and research policy. Technological proximity should be considered as one of the most important starting point for making policy and management decisions, because it has by far the strongest magnitude of effect on both the formation and the output of collaborations. Particularly, it has the highest marginal effect in our models: This means that it has the highest contribution to the variations in the independent variable which can be seen by removing and adding this variable in our models. As technological proximity has such positive effects on both the formation and the output of collaborations, measures of management and of policy that take technological proximity into account should have a substantial effect. Our findings suggest that university management and research policy should support existing collaborations between organizations being technologically diverse. The results show that the potential collaborators stay away from collaborations where the technological distance obstructs its success. As this is a good self-regulating mechanism management and policy should not stimulate starting collaborations that involve technologically distant partners. However, if technologically distant partners have already an ongoing relationship – according to our results – they are the more productive the more technologically distant they are. So, it is worth a while supporting these collaborations. Existing German policy measures, such as The Initiative Networks of Competence Germany which includes more than 9000 members from different technological fields (BMBF 2012) might be a useful starting point in this context. On top of that, one could think of web-based cluster portals and matching sites giving access to information about potential partners and various research initiatives. This would give potential partners sufficient information to decide whether or not to initiate a collaboration.

Our results on organizational proximity point to tailor-making research policy and university management in order to deal with the specific nature of the German innovation system. Our findings regarding organizational proximity and collaboration suggest that the non-university organizations, i.e. the institutes of the Max-Planck Society, of the Fraunhofer Society, of the Leibniz Association as well as the Helmholtz institutes, would benefit from overcoming organizational distance. As these organizations are extremely specialised with some organizations focusing on basic and some on applied research, having different goals and set-ups we suggest that research policy and university management focus on them. According to interviews with various stakeholders in German nanotechnology these barriers are threefold (Heinze and Kuhlmann 2008). One, there are a number of stereotypes and prejudices which suggest that scholars from specific organizations are slower or less productive than others. Two, due to different missions and set-ups the work working routines of the organizations are not compatible. Three, there is interface management amongst the headquarters of the different organizations in place. These barriers can be overcome by active management of joint projects between the different kinds of organizations. These projects should also align objectives of the different organizations. To establish interface management between the different kinds of organizations would also help in this context. The German Ministry for Education and Research already has established such projects for university-industry projects. To give an example, since 2003 it funded several value-chain oriented collaborative projects aiming at connecting the scientific community with the commercial world (Zweck et al. 2008). This experience can be used to bring together organizations from the non-academic sector as well. Within the organizations management of universities and research organizations would help collaborations by being offering flexible solutions for partnerships with other kinds of organizations.

Regarding physical and systemic proximity we suggest carefully considering the aim of policy and management measures. To give an example, if policy implements measures aimed at improving transport infrastructure measures then they may achieve a reduction in commuting time between potential partners. This would enhance the likelihood of them to form collaborations. However, the output of existing collaborations would not change. If policy intends an increase in collaboration output it would better invest in local knowledge infrastructure, thereby enhancing systemic proximity. Existing collaborations would benefit from knowledge and information in the local innovation system and therefore produce more publication output.

5. Conclusions

With our analysis we will get deeper insights into the dynamics of collaborations, i.e. the linking pins of knowledge transfer in key enabling technologies. While focusing on the influence of proximity on collaborations we divide collaboration into two processes or stages: the formation of a link between two parties and further maintenance of these relationships. Thereby, we suggest that getting to know people and maintaining relationships with them takes different kinds of proximity, i.e. physical, systemic, organizational and technological proximity. By doing so we shed more light on the nuances of how various forms of proximity enable the formation of a collaboration but also enhance the productivity of an existing collaboration. A failure to understand these nuances might lead to the wrong management and policy decisions and might negatively affect the development and deployment of nanotechnology.

In our research we analysed the influence of technological, organizational, physical and systemic proximity on two stages of collaboration in German nanotechnology: its formation and its output. While the influence of technological proximity on both the formation and the output of collaboration is considerable policy and management should be careful not to stimulate the formation of collaborations being technologically distant as self-regulation seems to avoid non-productive collaborations. For already existing collaborations they should particularly stimulate collaborations between technologically distant partners which are particularly fruitful. Organizational proximity increases the chances of collaboration for universities and decreases them for non-universities. This fact can be explained by the misalignment of objectives of German extra-university research centres like Max Planck or Fraunhofer. These conclusions are supported by an earlier analysis where stereotypes and prejudices in perceptions of scholars from different organizations, their incompatible working routines and lacking interface management between the different kinds of organizations proved to be core bottlenecks for fruitful collaborations between non-academic organizations (Heinze and Kuhlmann 2008). Therefore, we suggest that policy and management try to overcome these bottlenecks. Our results on physical and systemic proximity give more nuance to geographical proximity which has been investigated very thoroughly in the past. Obviously it helps forming a collaboration if scholars are working physically close to each other. The output of a collaboration remains unaffected though. However, working in the same NUTS3 region, i.e. level of Kreise, as well as neighbouring NUTS2 regions, i.e. within the same Land, positively influences the output of a collaboration but not its formation. Either systemic proximity on the district level captures the fact that people working within the same or neighbouring districts can meet face-to-face by normally traveling less than an hour. Or the indicator captures that scholars are socially close, i.e. they know each other previously or at least know someone who knows them.

Our results provide the basis for two further research lines. One, in this paper we focused on the scientific network of nanotechnology, i.e. scholars working at universities and mainly publicly funded non-university organizations. This is due to our focus on publication analysis. In further research we would like to complement publication with patent and other data - often found on the internet. That would enable us also include the industrial network, i.e. scholars working at nanotechnology firms. Two, we could detect that organizational and systemic proximity capture not only their effects on collaborations but also the nature of the German innovation system. Including more countries in our analysis would enable us to investigate these effects more thoroughly. Further investigations of regional and national innovation systems, in particular their role for nanotechnology collaborations, might be fruitful in this context. Particularly, comparative analyses of European countries' nanotechnology networks with that of other leading countries, such as the US, Japan or China might be promising.

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