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OLOGICAL, AND ORGANIZATIONAL PROXIMITY AND COLLABORATION IN EUROP

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Abstract

Proximity influences collaboration. This makes proximity a logical starting point for management and policy intervention in order to stimulate collaboration. In this paper, we analyze three types of proximity, namely organizational, technological and geographical proximity. The role of these proximities in stimulating collaboration is estimated with the help of a sample of European nanotechnology publications. While organizational proximity is significant it is the least important of the three kinds of proximity. Geographical proximity is most significant in statistical terms and technological proximity has the highest magnitude of effect. Consequently, the latter lends itself most for management and policy intervention.

Jelcodes:O33,O14

Proximity and Collaboration in European Nanotechnology

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Abstract:
Collaborations are particularly important for the development and deployment of technology. We analyze the influence of organizational, technological and geographical proximity on European nanotechnology collaborations with the help of a publication dataset and additional geographical information. While organizational proximity influences collaboration only indirectly geographical and technological proximity do so directly. Geographical proximity is most significant in statistical terms and technological proximity has the highest magnitude of effect. Consequently, the latter lends itself most for management and policy interventions, e.g. providing information on technological specialization of potential partners or on project management tools.

JEL Classification:
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Proximity, collaborations, nanotechnology, European Union, EFTA.

1. Introduction

Nanotechnology has emerged as a scientifically and economically major area of research. For decades it has been encompassing and infiltrating industries, regions, technologies and countries all over the world. Nanotechnology has had crucial impact on former and current technological development (Commission of the European Communities (CEC), 2009a, Bozeman et al., 2007, Islam and Miyazaki, 2009, Salerno et al., 2008). Its significant potential for technological change and for current and future world markets becomes obvious when looking at its market size and its growth potential. In 2009, the market size of products underpinned by nanotechnology was 254 billion US Dollars (Forfas, 2010). Its market size for 2015 is expected to reach almost the tenfold level of 2009 with 2.5 trillion US Dollars. All over the world nanotechnology has "… redefine(d) existing industries and array(ed) them in new combinations …" (Bozeman et al., 2007, 807). It has stimulated interdisciplinary and pervasive research and development (CEC, 2009a and Salerno et al., 2008). Consequently, the deployment of nanotechnology and related technologies has led to substantial changes in telecommunication, biotechnology, pharmaceuticals, precision mechanics etc. (Miyazaki and Islam 2007, CEC 2009a and b).

Collaborations are particularly important for the development and deployment of technologies (CEC, 2009a) as they represent knowledge transfer between collaboration partners in the production process of novelty. They benefit from different kinds of proximity which partly overlap and depend on each other. In the literature many kinds of proximity are discussed, e.g. organizational, technological, geographical, cognitive, sectorial, functional and social proximity (Boschma, 2005, Frenken et al., 2010, and Maggioni and Uberti, 2009, Petruzelli, 2008). Empirical investigations have shown that different types of proximity can overlap and be mutually dependent. In particular, former analyses suggest that the role of geographical proximity depends on the technological context. A study on science-based industries showed a quite diverse picture for geographical proximity as it does not play a role for all university-industry-government collaborations in all these industries: While in life sciences the citation impact of regional collaborations is higher, in physical sciences it is the international collaborations which have the highest publication impact (Frenken et al., 2010). A study about knowledge flows between regions of five European countries support this finding. It shows that geographical proximity determines the structure of inter-regional knowledge flows because knowledge flows easily between regions that are similar in terms of their scientific, technological and sectorial characteristics (Maggioni and Uberti, 2009).

In nanotechnology former research suggests that geographical and technological proximity plays a role. Little is known about the role of organizational proximity though. Geographically, for the U.S. there is evidence that nanotechnology concentrates on the regional level while maintaining substantial global ties. Here, regionally tied "nanodistricts" in the form of distinct types, such as government-dominated districts, university-dominated districts, and high technology districts have emerged (Shapira and Youtie, 2008). There have been very few investigations which have addressed organizational proximity (e.g. Petruzelli, 2008) and to our knowledge none which specifically concerns organizational aspects of collaboration in nanotechnology.

In this paper, we contribute to a better understanding of how organizational, technological and geographical proximity influence collaboration in European nanotechnology. A deeper understanding of knowledge transfer and innovation mitigated by proximity will help policy and management addressing nanotechnology issues in developing and deploying the potential of this important technology. The paper is organized as follows: First, we show which role European nanotechnology, i.e. research carried out in the EU and EFTA countries, has played globally (Section 2.). Then, we discuss collaboration and proximity in organizational, technological and geographical terms to build the hypotheses tested in this paper (Section 3.) Next, we introduce the data (Section 4.) Thereafter, we discuss the regression model, our results on proximity and collaboration and their implications for management and policy of nanotechnology (Section 5). We round the paper with a brief summary of our results and further research questions emerging from our analysis (Section 6.)

2. Nanotechnology in the EU and EFTA countries

Nanotechnology relates to a broad field of research and includes many areas of application, e.g. physics, chemistry and medicine. As a consequence, its delineation has been widely debated (e.g. Miyazaki and Islam, 2009). Defining nanotechnology and its constituent subcategories proves difficult, particularly when measuring research and development outputs (Porter, Youtie, Shapira and Schoeneck, 2008, and Huang et al., 2008). Generally speaking, nanotechnology is based on the idea that single atoms or molecules can be physically manipulated at the nanometer level (i.e. one-billionth of a meter). Often scholars distinguish between nanotechnology research and nanoscience (e.g. Miyazaki and Islam, 2009). Still others use nanotechnology as the synonym for both (e.g. CEC, 2009b, and Bozeman et al., 2007). The distinction between nanotechnology research and nanoscience is motivated by the traditional distinction between basic and applied research. This distinction suggests that the development of fundamental understanding and of practically usable results is the opposite ends of a continuum. However, pursuing fundamental understanding as well as finding practically usable results at the same time is not only possible but seems to be the most interesting part of activities in science and research (Stokes, 1997). Therefore, we will use nanotechnology as a synonym for nanotechnology research and nanoscience in our following analysis. We thereby acknowledge the fact that researching and developing nanostructures contribute to fundamental understanding as well as to practical use (e.g. Islam and Miyazaki, 2009).

Worldwide, the European Union (EU), the US and Japan are most active in nanotechnology. A comparison between these three areas shows that in 2004 the total EU investment on nanotechnology was less than € 2 billion, compared with almost € 3 billion invested in the US and € 2.3 billion in Japan (Hullmann, 2007). The public investment on nanotechnology was higher in the EU (€ 1.29 billion) than in the US (€ 1.24) though, accounting for the lesser private EU investment on nanotechnology. Investment is an input measure and does not mirror whether and how research input is translated into research output. Research output in terms of publication data suggests that the EU contributed almost as much to nanotechnology related publishing as the US (27%), which was the biggest single player; the third biggest player was Japan with 15% (Miyazaki and Islam, 2007). However, comparison between the three areas show that per capita the EU is investing and producing the least in nanotechnology, i.e. when taking into consideration that the EU has substantially more inhabitants (463.7 million inhabitants for the EU25, i.e. in the borders of 2004) compared to the US (295.7 million inhabitants in 2004) and Japan (127.4 million inhabitants in 2004) (CEC, 2007).

Our following analysis on European nanotechnology will include the twenty-seven EU countries (Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom) as well as the four European Free Trade Association (EFTA) countries (Iceland, Liechtenstein, Norway, Switzerland). There are two reasons for this: One, research in the EU and EFTA countries is closely connected, which is also mirrored in the involvement of the EFTA countries in EU research policy. While Iceland, Liechtenstein and Norway co-operate on research policy as part of the European Economic Area (EFTA, 2011) Switzerland does so via a bilateral agreement with the EU (Swiss Federal Department of Foreign Affairs, 2010). Two, particularly Switzerland contributes substantially to European research in nanotechnology and Swiss organizations are important collaborators in the European nanotechnology network.

In contrast to the US and Japan European nanotechnology activities are highly decentralized (CEC, 2009a and b). Therefore, networking is seen as being paramount for developing a critical mass of knowledge and economic activity. Within the EU and the EFTA countries public support of nanotechnology primarily stems from the member states, with only a fraction of the public support being financed by the EU as a whole (CEC, 2009a and b). Acknowledging the importance of nanotechnology the CEC implemented an action plan from 2005 until 2009 focusing on nanotechnology research funded under the 7th Framework Programme, on support of regulatory and standardisation activities and on the creation of a nanotechnology observatory (CEC, 2009b). Currently the CEC is developing a common strategy for nanotechnology as one of the core key enabling technologies in the EU (CEC, 2009a).

When looking at nanotechnology activities in a global context it becomes clear that European countries perform very differently. This is shown by Forfas, 2010. Their analysis is based on two measures: One, nanotechnology activity provides the absolute measure of a nation’s capabilities and resources for nanotechnology innovation, relying on indicators such as government funding for nanotechnology, number of patents, and number of publications. Two, technology development strength provides the relative measure of a nation’s technology commercialisation prowess. This measure shows how well-positioned a nation is to profit from scientific and technological advance in general terms. Here, indicators such as domestic output in high-tech manufacturing and science and technology work force were taken into consideration. European countries can be found all over the spectrum of the technology development strength/ nanotech activity grid.[4] In the dominant tier of nations, those with high nanotechnology activity as well as high technology development strength, the U.S. and Japan score highest, directly followed by Germany. In the ivory tower with high nanotechnology activity but low technology development strength we find the UK and France, which are already quite close to the dominant tier. UK and France show considerably less nanotechnology activities and fewer prowesses to commercialize the results of these activities than Germany though. Switzerland and Sweden can be found in the niche quadrant indicating that use their high general technology commercialisation to successfully carry out and apply research in specific areas of nanotechnology. The Netherlands and Italy are moving into the direction of the niche quadrant and might also reach the dominant quadrant in the nearer future. Currently, however they are in the minor league with neither high nanotechnology activities nor high technology development strength, together with Canada, Australia and Russia.

[4] The nations ranking grid was originally developed by Lux Research. Its current applications and results were obtained in joint research by Forfas and Lux Research and published in Forfas (2010).

3. Building hypotheses on proximity and collaboration

In the following, we investigate organizational, technological and geographical proximity to show their influence on European nanotechnology collaborations. Collaborations between researchers affiliated at different organizations represent a major exchange of knowledge between the partner organizations as well as production of new knowledge (Katz and Martin, 1997). We can observe collaborations in quite different forms, ranging from shared R&D projects, consultancy work, joint use of technical equipment, exchange of personnel between two partners, mobility of the workforce, education, provision of information via publications of scientific papers, patents to licensing agreements and spin-off entrepreneurship (D´Este and Patel, 2007, Fritsch et al., 2007, Jensen et al., 2007, Kauffeld-Monz and Fritsch, 2008, Bekkers and Bodas Freitas 2008).

Our major hypotheses suggest that collaborations do not emerge randomly. There is a considerable literature concerning the random formation of scientific collaboration networks though (Newman 2001). In line with this reasoning one could argue that collaboration is randomly distributed across the links of a network, or as a proportionate fraction of publication of one research organization. As a starting point we therefore formulate ***hypothesis zero***, i.e. *that collaboration in European nanotechnology is purely random.* To show the non-random character of collaborations we develop a number of hypotheses that contradict our hypothesis zero. With this we argue that, despite the complexity of networks which emerge from simple, random processes, the European nanotechnology collaboration network displays discernable features in organizational, technological and geographical terms.

Organizational proximity is defined as closeness in terms of managerial arrangement, either within or between organizations (Boschma, 2005, and Meister and Werker, 2004). It goes from low managerial proximity, i.e. independent agents with no ties, such as found on spot markets, to high managerial proximity with strong ties, such as found in hierarchies, e.g. universities, research organizations and firms. To our knowledge the influence of organizational proximity on collaborations has only been rarely investigated.

Related work examined the consequences of differing organizational schemas on technological transfer (Bozeman 2000). For one university Petruzelli (2008) could show how proximity dimensions affect the establishment of different knowledge relationships between this university and other organizations (Petruzelli, 2008). The results indicate that exploitative collaborations, i.e. collaborations deploying existing technologies, benefitted from geographical, organizational and technological proximity. In contrast, explorative collaborations, i.e. collaborations pushing technological frontiers, profited from technological distance.

Organizational proximity might help when collaborating because of a shared cognitive background and easier knowledge transfer and coordination (Boschma, 2005). However, collaborators can be too close organizationally. In particular, diverse partnerships may prevent lock-ins which hampers the collaborators' ability to include additional information from the outside world in a creative and flexible way (Grabher, 1993). We do not consider lock-ins emerging from too much organizational closeness in the following analysis because of two reasons: One, we analyse collaborations with the help of publication data. Lock-ins in these kinds of collaborations are very unlikely because authors of papers have to refer to former findings of other researchers and to consider the comments of reviewers in order to get published their papers. Two, we only investigate collaborations with authors from different affiliations, which by definition makes too much organizational closeness unlikely. As a consequence, we concentrate on the positive effect of organizational proximity in our ***hypothesis one*** by suggesting that *collaboration is positively influenced by organizational proximity.*

Technological proximity is a part of cognitive proximity, which is the shared knowledge base of different agents. Agents need cognitive proximity in order to successfully "… communicate, absorb, understand and process new information" (Boschma, 2005, 64). In particular, technological proximity mitigates collaborations that rely on shared technological experiences and knowledge bases (Knoben and Oerlemans, 2006). Former investigations show the importance of technological proximity for collaborations, because agents need to be sufficiently similar in their technological knowledge bases in order to see the opportunities stemming from other agent's knowledge bases (Colombo, 2003). At the same time they need to be different enough to combine different knowledge in creative and novel ways. When agents are very different in their knowledge bases there is a lot be learnt but also learning is more difficult. In line with these considerations we convey ***hypothesis two***, namely *that collaborators benefit most from technological proximity when being technologically distant but not too distant*.

Geographical proximity can be crucial for collaborations. In the following, we define geographical proximity in two ways. One, we look into the pure spatial or physical proximity of economic actors (Boschma, 2005, and Meister and Werker, 2004). Two, we analyse the functional closeness of economic actors. Functional closeness can exist on the regional, national and global level. On the national and sometimes on the supra-national (e.g. EU-) level economic actors are close because they rely on the set-up and functioning of formal institutions, i.e. legislation, which mostly stems from these more aggregated levels (Metcalfe, 2005, and CEC, 2009a and b). On the regional level economic actors are close because of cultural aspects and informal rules influencing their collaborations (Werker and Athreye, 2004). Intraregional knowledge transfer is important because agents share not only the same cultural background and closely-knitted networks but often are specialised in similar or closely connected technologies. Here, the systemic role of regions in knowledge production is crucial as agglomeration of economic activities is advantageous for the exchange of tacit knowledge (Cooke et al., 1997). Thus, regions do more than merely enhance knowledge exchange – they reduce the transaction costs associated with the exchange of knowledge. In accordance with the two kinds of geographical proximity we formulate two hypotheses on the influence of geography on collaborations. ***Hypothesis three*** suggests *that collaborations benefit from the sheer physical closeness (measured in km of distance)*. ***Hypothesis four*** advocates that *collaborations benefit from the functional closeness of regions (measured by being within the same unit of region, i.e. NUTS regions).*

As will be shown in section 5. the regression model includes collaboration as the dependent variable, the organizational, technological and geographical proximity as the independent variables as well as a number of parameters and dummies.

4. Measuring proximity and collaboration in nanotechnology

4.1 Using publication data

Many of the indicators we use in the following are based on publication data and are as such output indicators. In the following, we use scientific collaboration as a proxy for knowledge exchange. Katz and Martin (1997) discuss the substantial efforts required to facilitate inter-organizational collaboration in science, and argue that multiple affiliations on a paper are substantive indicators of knowledge sharing. Publications are a partial, incomplete measure of collaboration and exchange. Nonetheless such an indicator may provide valuable insights into the working of collaborations, particularly in science-based industries such as nanotechnology. Frenken et al. (2010) also investigate collaborations in science-based industries, albeit with a different dependent variable than proposed here.

Looking at publication data comes with the usual caveats (e.g. Nelson, 2009). In particular, publication data do not cover research activities that are not published, thereby e.g. underestimating the efforts of small and medium sized companies as well as of industries, which traditionally rely on secrecy to keep their ideas from being copied. However, in medium-sized companies with an own R&D department it is quite normal that the staff publishes their results. Moreover, the secrecy networks are by nature closed and do not contribute much to knowledge transfer within the overall networks anyway. Another caveat concerns the fact that the affiliations mentioned on the papers may not be the places where the actual research was done, either due to change of affiliation or due to a habit to publish under the address of the headquarters or of the research facilities. To our knowledge there is no way to correct for this. Therefore we use the information on affiliations given on the papers as a proxy for the place where the actual research was carried out.

4.2 Nanotechnology in the Web of Science

We use the nanotechnology related sub-set of data from the Web of Science. The Web of Science is a product offered by Thomson Reuters, covers ten thousand high impact journals worldwide and includes 256 disciplines (Thomson Reuters, 2011). Each journal in the data is assigned one or more subject categories by Thomson Reuters. Amongst others the database contains abstracts, keywords, the names of authors and their organizational affiliations. Our subset concerns nanotechnology, which can be defined as technology on the nanoscale (see for details Section 2.) or in terms of Boolean database queries. Porter, Youtie, Shapira and Schoeneck, 2008, identified the nanotechnology related abstracts in the ISI database of science by a careful query design that was developed in consultation with nanotechnology experts. To identify nanotechnology in the overall Web of Science we execute the aforementioned Porter query. In a nutshell, the Porter query looks for significant nanotechnology research that is concentrated across six main Web of Science subject categories. These include two fields of physics (applied physics and condensed matter), two fields of chemistry (physical chemistry and multidisciplinary chemistry), materials science (multidisciplinary materials science), as well as nanoscience and nanotechnology. The multidisciplinary content in the subject categories chemistry and materials science suggests an emerging new field of research. As a result of executing the Porter query we got more than 830,000 papers on nanotechnology published between 1988 and 2009. These papers constitute a significant fraction of world scientific research as estimates suggest that 7% of all research articles are nanotechnology related.

The subset of the database that we will use in the following contains more than 14,000 abstracts of nanotechnology related papers, published from 2008 until 2009. Although data would be available for the period 1990 until 2009 the data before 2008 is partial or incomplete regarding the organizational addresses. Up till 1994 the Web of Science data provided only the organizational address of the leading author. In subsequent years from 1994 until 2007, all organizations are reported. However, in these years the data fails to provide an unambiguous mapping between the list of authors, and the list of affiliations, so that it is unclear which authors resided where. In the most recent years, beginning with some papers in 2007, the Web of Science data provides an unambiguous mapping between the author and their affiliation. As a consequence we use the data where we can directly connect every author with a specific affiliation, i.e. data from 2008 until 2009. Concentrating our analysis on the data of 2008/2009 means that we draw a quite recent picture of European collaborations in nanotechnology and are able to unambiguously relate the authors to geographical places.

To appropriately credit collaboration there are several options for fractionating publications. In this paper we first divide the credit for the paper equally across all authors, and then award the respective organizations according to the affiliations of the authors. A comparable scheme for fractionating co-patenting activities was used in Maggioni et al. (2007).

4.3 The sub-sample of European nanotechnology collaborations

In the following, we investigate the one hundred most productive European organizations in the field of nanotechnology, i.e. those with at least one author affiliated in the EU or in the EFTA countries (for the discussion of the geographical delineation see Section 2.). They account for about 40% of the European total number of publications.

We prepared the data in the following way: We started by disambiguating the names of the organizations in the database in order to capture all information on the top one hundred European organizations. This was necessary as the organizations are often using different names, e.g. Delft University of Technology, Technische Universiteit Delft and TU Delft all refer to the same organization. After the disambiguation we apportion research to participating organizations according to total authorship. For instance, an organization which contributes two out of five total authors receives a 40% credit for the paper as a whole. Our sample is bigger than it likes at the first sight, because a paper might be written by one collaborator from the top 100 European organizations and one collaborator from a non top 100 European organization or a non European organization. Our sample is smaller than it likes at the first sight, because we do not include intra-organizational collaborations, i.e. we omit papers written by authors from the same organization. Although internal collaboration within organizations is an important phenomenon it is not the object of this particular study.

We complemented the data of the one hundred most productive European organizations in nanotechnology related publications with organizational, technological and geographical information. We added *organizational information* by classifying each organization according to its academic or non-academic character. Inter-organizational collaborations can take place between partners stemming both from an academic background (academic/academic) or both from a non-academic background (non-academic/non-academic) or from a mixed academic and non-academic background (hybrid). We consider collaborators from universities and related organizations (e.g. the Max-Planck-Institutes in Germany) as having an academic background and those from firms having a non-academic background (see for a similar approach Frenken et al., 2010). Closest in terms of organizational proximity are collaborations with partners from a similar background, i.e. academic/academic and non-academic/non-academic. Hybrid collaborations show the largest organizational distance. We added *technological information* by calculating a technological research profile of each organization. To do so, we use the six major nanotechnology subject categories provided by the Porter query (for details see section 4.2. and Porter, Youtie, Shapira and Schoeneck, 2008) and an "all others" category. The more overlap two organizations have in terms of this profile the closer they are technologically. We completed the information retrieved from the Web of Science by *geographical information* in two ways. First, we geo-located each organization using Google Earth, i.e. we collected the longitude and latitude for each organization, stored in fractions of a degree (Google Earth, 2011). Second, we related each organization to the NUTS (Nomenclature of Territorial Units for Statistics) system by using the three levels NUTS 1, NUTS 2, and NUTS 3 (Eurostat, 2011). NUTS 1 relates to major socio-economic regions (e.g. Länder in Germany or regions in Belgium), NUTS 2 to more disaggregated units often used for implementing specific regional measures (e.g. counties in the UK, regions in Romania or provinces in Belgium and the Netherlands) and NUTS 3 to small regions that are used for specific diagnosis, such as unemployment figures (e.g. departments in France or cantons in Switzerland).

Figure 1 demonstrates the strong regional structuring of European nanotechnology districts at the NUTS 2 level. This figure maps the top 100 collaborators according to their NUTS 2 region. The regional structuring is partially following the famous "blue banana" (e.g. Hospers, 2003) reaching from the UK, namely Liverpool London, down through the Netherlands, large parts of Germany, Zurich (Switzerland) and North-Italy. For nanotechnology research the "blue banana" is extended by the arc which reaches from North-Italy through the Occitania region of France and onwards to Valencia (Spain). In addition, we see the swath of research activity reaching from Copenhagen onwards through Sweden and Finland. To a large extent Figure 1 confirms the results of former studies on nanotechnology that saw Germany in the dominant tier of nanotechnology activities, the UK and France quite close to it, and Switzerland and Italy establishing themselves in nanotechnology niche markets (for details see Section 2.).

Figure 1 about here

5. Findings and implications for European nanotechnology

With the help of publication data from the Web of science, geographical data from Google Earth and from EU geocode standard NUTS (see Section 4.) we analyse proximity and collaboration in European nanotechnology. First, we show the specification of the regression model (Section 5.1). Then, we turn to the model results discussing the influence of organizational, technological, and geographical proximity on European collaboration in nanotechnology (Section 5.2).

5.1 The specification of the regression model

We use a log-linear regression model with collaboration intensity as the dependent variable. Collaboration intensity is the total amount of co-publication conducted between two organizations. Since publication count and co-publication are fractional quantities per organization, this is a ratio-scaled variable. When calculating collaboration intensity we consider all possible external collaborations between the one hundred collaborators, i.e. 4,950 potential collaborations. For the collaborations, which are not taking place, the collaboration intensity measure is zero.

The independent variables used in our regression analysis represent organizational proximity, technological proximity, and geographical proximity. For *organizational proximity* we included two dummy variables, acad and nonacad, in the model. A collaboration scores 1 on the acad variable if there is at least one academic partner. A collaboration scores 1 on the nonacad variable if there is at least one non-academic partner. In order to control for the different ability of academic and non-academic organizations to broker technological proximity we use the interaction terms: non-academic information (nai) and non-academic information squared (naisqr) which are scored only when there are collaborations involving at least one non-academic partner.

To measure *technological proximity* we collected a research profile for each of the potential 4,950 collaborations (for details see Section 4.2). We calculated this profile based on external collaboration between each two organizations. In cases where no external collaboration between two organizations took place we replaced the profile with the average profile of all nanotechnology research in the database. Our goal is to produce a measure of the difference in the profile of research conducted internally and externally. One measure which converts internal and external profiles into a single measure of distance is mutual information (info). We also include an interaction term (infosqr) to account for the potential non-linear effect. Technological proximity is calculated as follows:

$$\mathrm{INFO}(x,y) = \sum_{i\in I}\sum_{i\in I} p(x,y)\log\left(\frac{p(x,y)}{p(x)p(y)}\right) \tag{1}$$

This well-known formula relates to the mathematical theory of communication (Shannon 1948), and is extensively discussed throughout the discipline of information theory (c.f. McKay 2003). The mutual information of the research profiles of organization x and y is calculated by considering each subject category i in the larger set of nanotechnology relevant subject categories. The calculation considers both the profile of research done individually, i.e. p(x) and p(y), as well as mutually, i.e. p(x,y). If organizations share the same research profile technological distance between them is zero. In theory, the distance could climb to infinity. In this sample though, the catch all category of "everything else" ensures at least a minimum amount of technological proximity. In the following, we use the unit of technological proximity in 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.

We decomposed *geographical proximity* into physical and functional proximity. Physical proximity is measured by the great circle distance in organizations between two organizations. Functional proximity is measured by shared NUTS regions (region), as well as by bordering NUTS regions (border) measured at all three NUTS levels. We thereby capture not only the pure distance in km but also the distance in functions of geographical proximity. We suggest that knowledge transfer benefits from belonging to the same region on top of the pure physical km distance. Therefore, we include three interaction terms between regions and distances in the regression, namely the interaction between NUTS 1 regions and distance and the interactions with distance at the NUTS 2 level as well as at the NUTS 3 level.

In addition to the independent variables discussed above we include three control variables, namely total earned publication (publication), total earned citations (citation), and total number of partners in collaborations (partners). These are measured by organization, across the entirety of all partnerships and publications. The number of publications and citations help us indicating scientific excellence in nanotechnology. In the literature the numbers of publications are normally used to quantify the output and the number of citations to indicate the quality of the papers (e.g. Katz and Martin, 1997, and Hullmann, 2007).[5]

The homogenization of parameters and the link function used to relate dependent and independent variables we describe as follows. As there is no natural ordering to the data we homogenize parameters which are solely dependent on single organizations. This includes the variables of partnership, publication and citation. The data for each of the organizations is averaged; this is a maximum likelihood technique for estimating a common effect across partnerships and their ordering. We also take the logarithm of ratio-scaled, non-zero variables in the data. This includes distance, partnership, publication, and citation. The dependent variable is predicted by the linear, non-linear and interaction terms discussed above, subject to a quantity of noise.

The regression model contains the depend variable Y, i.e. collaboration intensity, the independent variables representing organizational, technological and geographical proximity, and some interaction terms and control variables (for details see Appendix A). Model 1 includes the dependent variable, all independent variables, all parameters and dummies like indicated in Section 5.1. The resulting specification is a log-linear regression model.

$$Y = b_0 + b_i X_i + \varepsilon \tag{2}$$

Model 1 and 2 differ with respect to the variables and the parameter that turn out insignificant in Model 1. As a precaution against misspecification the insignificant variables and parameters are omitted in Model 2.

[5] This is notwithstanding the fact that some citations are referring to papers that are criticized. However, the majority of citations refers to work that is related to the work presented or on which this work is built. So, following e.g. Katz and Martin, 1997, and Hullmann, 2007, we consider the number of citations as quality measure.

5.2 The results on proximity and collaboration in European nanotechnology

In the following we present the results of the two regression models which are similar. Model 1 has an adjusted R-squared of 44.6%, with an F-statistic for the model of 251 (see Annex B). These statistics are significant with a p value of less than 0.001. Most, but not all, of the parameters are significant at a level of p less than 0.05. The principal exceptions are the basic organizational proximity variables (acad and nonacad), and the partnership control variable (partners). Model 2 skips these two non-significant variables and the non-significant parameter. In Model 2 the R-squared and standard estimate are not significantly altered, which is as would be expected when dropping statistically insignificant variables (see Annex C). Likewise, the associated F-test has increased, since there are correspondingly higher degrees of freedom in the regression. All variables are significant at a p value of $p = 0.01$ or lower.

The most important results of the regression analysis are summarized in Table 1. The complete results of Model 1 are presented in Appendix B and those of Model 2 in Appendix C. Table 1 groups variables by type of proximity (geographic, organizational, organizational-technological, and technological) and includes three control variables. We are fully able to discount hypothesis zero suggesting that collaborations in European nanotechnology is random. While we could not support ***hypothesis one*** on organizational proximity we could find evidence for ***hypothesis two*** on technological proximity as well as for ***hypotheses three and four*** on geographical proximity. We found that organizational proximity affects collaborations depending on the kind of organizational and technological profile of the collaboration partners involved though.

Table 1 about here

Regarding *organizational proximity* we could not find support for ***hypothesis one***, which suggested a direct influence on collaboration: Neither exclusively academic, exclusively non-academic, nor mixed forms of collaboration are significantly different in terms of output. However, when looking at the question whether organizations mediate technological proximity differently, we can detect an indirect effect, namely that academic collaborators are much better able to mediate technological distance. As noted above, the model includes interaction terms between non-academic collaborations and information. These interaction terms demonstrate that academic and non-academic partnerships mediate technological proximity differently. Non-academic partnerships achieve a higher marginal productivity given relatively proximal technological partners. Academic partnerships achieve a higher productivity overall. At six hartleys and beyond, academic partnerships are more likely to produce publication outputs than their non-academic and mixed partnership equivalents.

Technological proximity plays a considerable role for European collaborations. We could confirm ***hypothesis two*** suggesting that the collaborators have to be sufficiently different to benefit from each others' knowledge and sufficiently similar in order to understand each other (see Figure 2). Technological proximity has the highest effect of all variables in the model, as judged by the standard coefficients. The positive effects of technological distance are seen in the regression coefficient (info). As previously discussed this effect is presumed to occur because collaborators with distinct knowledge bases find collaboration more beneficial than two collaborators sharing the same knowledge. The negative effects of technological distance are seen in the non-linear term (infosqr) of the regression equation. After a critical point the differences between knowledge bases begin to mount, and shut down the benefits of collaboration. This negative effect is postulated to occur because of competing theoretical or methodological frameworks which inhibit shared understanding of research.

A comprehensive overview of the marginal effects of technological proximity is given in Figure 2 below. We may set the marginal productivity of 0 (complete technological proximity) to 100% with no loss of generality. Marginal productivity for all partnerships (given on the curve marked All) climbs until three hartleys are reached. Then productivity begins to diminish. Positive marginal contributions to collaboration are lost around five hartleys; collaboration is effectively unworkable by eleven hartleys.

Figure 2 about here

Geographical proximity boosts collaboration intensity. Pure physical proximity has a positive effect on collaboration intensity, thereby confirming ***hypothesis three***. Above and beyond the effects of pure physical distance, collaboration is also enhanced by functional proximity, i.e. ***hypothesis four*** is confirmed as well. The smaller the geographical unit, the greater is the enhancement to productivity. Significant productivity enhancements are seen at the NUTS 3, to a lesser extent at the NUTS 2, and even to a lesser extent at the NUTS 1 level. The effects of distance are also highly policy significant. This can be seen by examining the highest, and average, distances between organizations in the sample. The most distant two collaborators in the sample can expect to produce less than half the scientific output of others in the sample. Significant interactions of distance and regions are also seen in the model. Collaborators sharing the same NUTS 3 region effectively suffer no negative externalities for distance. This is seen by comparing the interaction terms (region1, region2, region3) with the coefficient of distance (distance). Nearly 80% of the externalities of distance are alleviated by organizations in the same NUTS 2 region. Even at the highest level of the state, the NUTS 1 region alleviates nearly half of the negative effects of distance on collaboration.

The effects of control variables on collaboration intensity are as follows. The first of the significant control variables is publication. We discuss the results starting from a simple null hypothesis that collaborations were allocated proportionally to productive output. This hypothesis would result in a publication coefficient of 0.500. A coefficient higher than 0.500 would indicate that collaborators are differentially focused on collaborations high-publishing partners. This is an assortative case. A coefficient lower than 0.500 would indicate that collaborations occurred preferentially with lower publishing partners. This case is the disassortative case. A coefficient not significantly different from zero would suggest that there is no effect of prior publication on intensity. The model evidences disassortative relationships between partners. There is a small, significant positive relationship of prior publication on intensity, all things considered. The standardized coefficient suggests that the effect is relatively small. The other significant control variable is citation. Highly cited organizations, all things considered, produce less in external collaboration than other organizations. An explanation might be that these organizations rely on greater internal knowledge assets and have more incentives to keep the rewards of publication internal to the organization.

5.3 The implications for management and policy

In European countries collaboration is even more important for the development and deployment of nanotechnology than for the US and Japan. The reason for this is that European countries are much more decentralized regarding the organisation and funding of research in general and nanotechnology research in particular (CEC, 2009 a and b). In this light, we discuss the results of our analysis on the influence of proximity on collaboration intensity in European nanotechnology. We focus on the question how management and policy can stimulate and support successful collaborations in European nanotechnology.

Geographical proximity was statistically most significant and technological proximity was politically most significant. It is possible to distinguish between analytic results which are statistically significant and analytic results which have policy significance (McCloskey and Ziliak, 1996). To determine the statistically most significant variable we looked into their marginal contributions to the regression model by adding them with or without the other explanatory variables in the framework. From this exercise geographical proximity turns out to be statistically most significant. In contrast, technological proximity shows the most policy significance. This can be shown by evaluating the beta coefficients in the equations. The beta coefficients allow a scale-free comparison between variables of dramatically different scale. The importance of technological distance is also directly apparent from the regression results. An appropriate choice of technological distance between partners can transform a collaborative relationship from one which would be otherwise untenable to one which is highly productive.

As technological proximity has the highest magnitude of effect we suggest that management and policy focus their interventions on this variable. They can do so via different channels. One would be policy initiatives that help finding collaboration partners with a fitting technological profile. The technological profile of two collaboration partners fit when they are at the same time sufficiently dissimilar in order to learn from each other and sufficiently similar in order to still understand each other (see Section 5.2 and in particular Figure 2 for this). A prominent example in this line is the Cordis Partner Service, offered by the European Commission (Cordis, 2011). Here, everyone can publish their own profiles and search for the profile of potential partners according to the field of activity, the country etc. Another way of using technological proximity in collaborations would be to stimulate multidisciplinary research. Multidisciplinary activity has been regarded as a necessary precursor for scientific progress (e.g. Porter, Roessner and Heberger, 2008). Our findings, which emphasize the policy significance of technological proximity in terms of being technologically close but not too close, hint at the importance of stimulating multidisciplinary collaborations. Recent non-governmental initiatives, for instance of the Keck Foundation, have focused on stimulating multidisciplinary and interdisciplinary research (Keck Foundation, 2011). Our results indicate that similar policy initiatives would have positive effects on collaborations and their productivity as well. Another way of intervening regarding technological proximity would be via management of universities and firms. They can support existing partnerships by helping to maintain them effectively and efficiently, e.g. by providing project management tools.

Geographical proximity is statistically most significant and therefore also lends itself as starting point for management and policy. It influences collaborations intensity in two ways: one, collaborations benefit from geographical closeness in terms of pure physical distance. And two, collaborations benefit from geographical proximity in functional terms, i.e. belonging to the same unit of administration such as NUTS regions. Pure physical distance can be more easily overcome by improving the road and telecommunication infrastructure works. Therefore, infrastructure measures of all kinds in regions that are less developed and connected are certainly welcome. Functional distance is not so easily accessible for management and policy. However, administration units can provide similar formal institutions and a network of administrators familiar with members of the research community. If the community of policy makers and the community of researchers are sufficiently connected administrators can instil trust in collaborations of research partners who are unfamiliar with each other in the beginning of their collaboration. This approach has been discussed in more detail under the keyword Triple Helix (Etzkowitz and Leydesdorff, 2000).

Organizational distance does not affect the productivity of collaborations directly but indirectly in a way that is interesting for managers and policy makers. The type of organization involved differs in their uptake of new knowledge: Academic organizations can successfully broker relationships across a wider range of potential topics, while non-academic organizations are more productive, but also more specialized in their technological and collaborative interactions. An explanation for this result is that compared to non-university staff university staff has access to a much broacher range of technological fields. This particularly holds for situations, in which academic staff might not have collaborated with someone in the other academic organization in the past. In academia the common cultural background of doing research, the clear view on the academic research community and the potential punishment for misusing someone’s trust that might lead to complete isolation help in this context. At the same time university staff does not benefit so much from specialisation, because their incentives are more related to creativity and novelty and less to efficiency. Thus, it might be valuable to support all kinds of collaborations, i.e. pure academic ones for mediating between different technological fields, pure non-academic ones for productivity and hybrid ones to cross-fertilize. While policy measures often show this kind of diverse approach it lies in the nature of management of academic and non-academic organizations to focus on their own activities. However, in case the policy measures, in particular the financial incentives, are strong enough management will take this diverse approach on collaboration on board.

6. Conclusions

In this paper we analyse how different kinds of proximity influence collaborations in European nanotechnology. We sought explanations for why some research collaborations were much more productive than others, while other potential collaborations remained untapped and unexploited. To do so we investigated a subsample comprising the one hundred top European organizations publishing on nanotechnology. The regression model we used considered geographical, technological, and organizational proximity as explanatory variables influencing collaboration intensity. These variables have been previously studied and our results are in line with former analyses. Here, we make new contributions by analysing the combined and marginal effects of different proximity variables on collaboration intensity.

We were fully able to discount hypothesis zero suggesting that the European collaboration network in nanotechnology is exclusively random in its structure. In fact, elements of geographical, technological and organizational proximity play an important role in understanding the structure of the network and the magnitude of collaborations which are apparent in the network. We confirm the hypothesis that geography plays an important role in shaping the network. The effects are both based on distance as geography plays a role in terms of physical distance and in terms of belonging to the same functional unit. Apparently, belonging to the same functional unit, e.g. to the same province, reduces the transaction costs normally associated with collaboration at a distance. Our hypothesis of technological proximity was upheld. Organizations seek out partners with an optimum amount of knowledge overlap – neither too close, nor too distant. The hypotheses concerning organizational proximity were partly upheld. All things considered, there are no significant differences in productive collaborative output between academic and non-academic organizations in the sample. However, the regression model shows that organizational types differ in their uptake of new knowledge. While academic organizations can successfully broker relationships across a wider range of potential topics, non-academic organizations are more productive, but also more specialized in their technological and collaborative interactions.

Policy and management of large research organizations have been interested in how to effectively and efficiently stimulate collaborations. We can show that the collaboration intensity, a measure for the productivity of collaborations, benefit from all three kinds of proximity investigated. Measures influencing the productivity of collaboration via the three kinds of proximity differ though. Technological proximity turned out to be most policy significant. Here, management and policy can help with providing information on potential partners and their profiles, e.g. specialised databases to find partners. Geographical proximity can be improved by infrastructure measures and better functional connectedness of the policy and research community. Regarding organizational proximity our results indicate that is important to rely on various kinds of collaborations, i.e. purely academic, purely non-academic and hybrid, in order to benefit from the advantages of all constellations.

A number of questions which go beyond the scope of this paper emerged from our results. In particular, there are three noteworthy lines of research: One, by employing social network analysis we would be able to identify the key players and clustering of activities in the overall European nanotechnology network. Two, our results indicate that the networks of collaboration partners have a quite distinct geographical pattern. Therefore, an analysis of these networks in terms of regional, national and global partners would be fruitful. Three, it would be interesting to compare the European nanotechnology research network with that of the US and Japan, because the three areas organize and fund research of nanotechnology in so different ways. Investigating these three lines of research would help to even better understand the functioning of nanotechnology collaborations and determine promising starting points for management and policy in this challenging and promising field.

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Appendix A: Overview of Variables used in the Models 1 and 2

Model 1 contains all variables listed below. For Model 2 we skipped the *variables in italics*, because they turned out insignificant when calculating Model 1.

Variable	Name	Description
Y	Publication	
X_1	Distance	Logarithm of great circle distance between collaborators
X_2	Region1	Logical variable indicating shared NUTS 1 region
X_3	Region2	Logical variable indicating shared NUTS 2 region
X_4	Region3	Logical variable indicating shared NUTS 3 region
X_5	Border1	Logical variable indicating collaborators share bordering NUTS1 region
X_6	Border2	Logical variable indicating collaborators share bordering NUTS2 region
X_7	Border3	Logical variable indicating collaborators share bordering NUTS3 region
X_8	Borderd1	Interaction term between distance and Region1 variables
X_9	Borderd2	Interaction term between distance and Region2 variables
X_{10}	Borderd3	Interaction term between distance and Region3 variables
X_{11}	*Acad*	*Logical variable indicating one of the collaborators is academic*
X_{12}	*Nonacad*	*Logical variable indicating one of the collaborators is non-academic*
X_{13}	NAInfo	Interaction term between non-academic collaborations and mutual information
X_{14}	NAInfosqr	Interaction term, non-academic collaborations and squared mutual information
X_{15}	Info	Mutual information of research profiles, a measure of dissimilarity
X_{16}	Infosqr	The square of mutual information
X_{17}	Publication	The average of the logarithm of the total publication of the two collaborators
X_{18}	Citation	The average of the logarithm of the total citation of the two collaborators
X_{19}	*Partners*	*The average of the logarithm of the total partnerships of the two collaborators*

Appendix B: Complete Results of Model 1

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.670a	.448	.446	.514

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1081.178	19	56.904	215.184	.000[a]
	Residual	1330.152	5030	.264		
	Total	2411.330	5049			

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	2.721	.232		11.735	.000
	Distance	-.432	.022	-.514	-19.890	.000
	Region1	.362	.067	.067	5.382	.000
	Region2	2.324	.176	.221	13.172	.000
	Region3	2.411	.223	.170	10.824	.000
	Border1	-1.393	.203	-.843	-6.858	.000
	Border2	-1.071	.158	-.768	-6.776	.000
	Border3	-.818	.178	-.379	-4.600	.000
	Borderd1	.197	.029	.822	6.731	.000
	Borderd2	.151	.023	.733	6.488	.000
	Borderd3	.118	.026	.367	4.454	.000
	Acad	-.008	.079	-.001	-.099	.921
	Nonacad	.002	.045	.001	.050	.960
	Info	.237	.017	.856	14.039	.000
	Infosqr	-.044	.003	-1.042	-16.739	.000
	NAInfo	.072	.038	.195	1.914	.056
	NAInfosqr	-.013	.006	-.205	-2.316	.021
	Publication	.266	.052	.116	5.141	.000
	Citation	-.096	.042	-.055	-2.284	.022
	Partners	-.074	.043	-.026	-1.732	.083

Appendix C: Complete Results of Model 2

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
2	.669	.448	.446	.514

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1080.384	16	67.524	255.343	.000[a]
	Residual	1330.946	5033	.264		
	Total	2411.330	5049			

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	2.595	.207		12.568	.000
	Distance	-.429	.022	-.511	-19.818	.000
	Region1	.367	.067	.067	5.445	.000
	Region2	2.323	.176	.221	13.173	.000
	Region3	2.425	.223	.171	10.896	.000
	Border1	-1.384	.203	-.838	-6.817	.000
	Border2	-1.079	.158	-.774	-6.828	.000
	Border3	-.820	.178	-.380	-4.608	.000
	Borderd1	.196	.029	.819	6.706	.000
	Borderd2	.152	.023	.737	6.524	.000
	Borderd3	.118	.026	.368	4.470	.000
	Info	.238	.016	.857	14.419	.000
	Infosqr	-.044	.003	-1.040	-16.947	.000
	NAInfo	.073	.027	.198	2.680	.007
	NAInfosqr	-.013	.005	-.208	-2.818	.005
	Publication	.254	.051	.111	5.012	.000
	Citation	-.117	.040	-.067	-2.959	.003

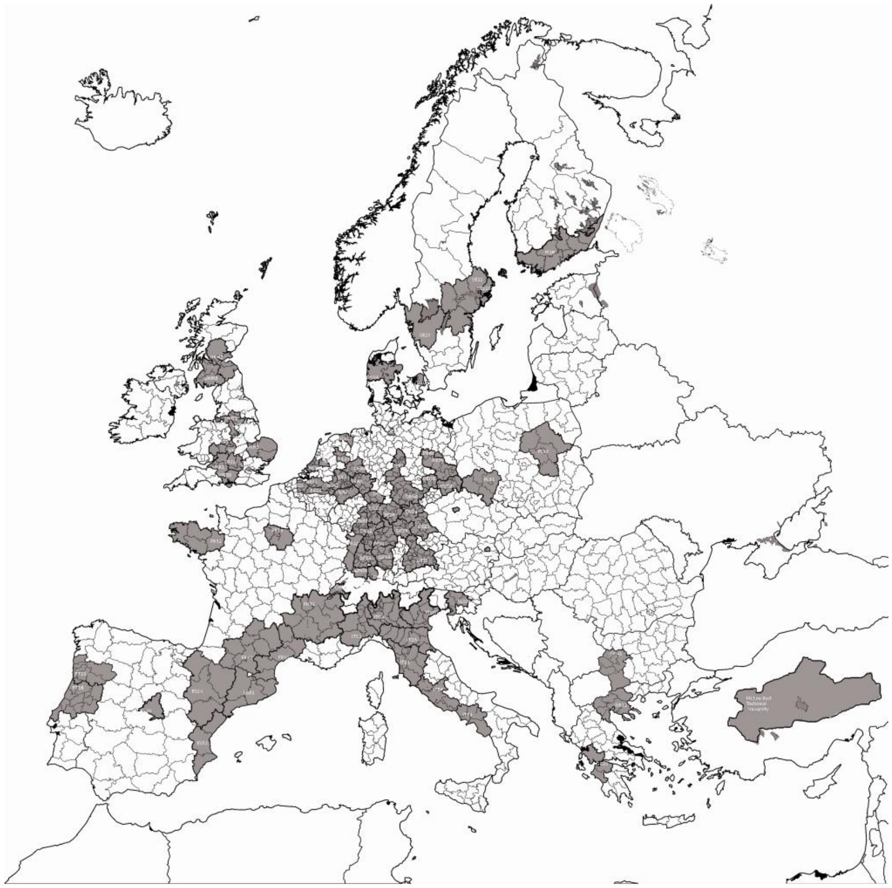

Figure 1: Leading nanotechnology regions in Europe

Name of the variable	Description of the variable	Significance + = positive - = negative 0 = insignificant
	Geographic Variables	
Distance	Logarithm of great circle distance between collaborators	-
Region1	Logical variable indicating shared NUTS 1 region	+
Region2	Logical variable indicating shared NUTS 2 region	+
Region3	Logical variable indicating shared NUTS 3 region	+
	Organizational variables	
Acad	Logical variable indicating one of the collaborators is academic	0
Nonacad	Logical variable indicating one of the collaborators is non-academic	0
	Organizational-technological variables	
NAInfo	Mutual information of research profiles, a measure of dissimilarity	+
NAInfosqr	The square of mutual information	-
	Technological variables	
Info	Mutual information of research profiles, a measure of dissimilarity	+
Infosqr	The square of mutual information	-
	Control variables	
Publication	The average of the logarithm of the total publication of the two collaborators	+
Citation	The average of the logarithm of the total citation of the two collaborators	-
Partners	The average of the logarithm of the total partnerships of the two collaborators	0

Table 1: Summary of the regression results

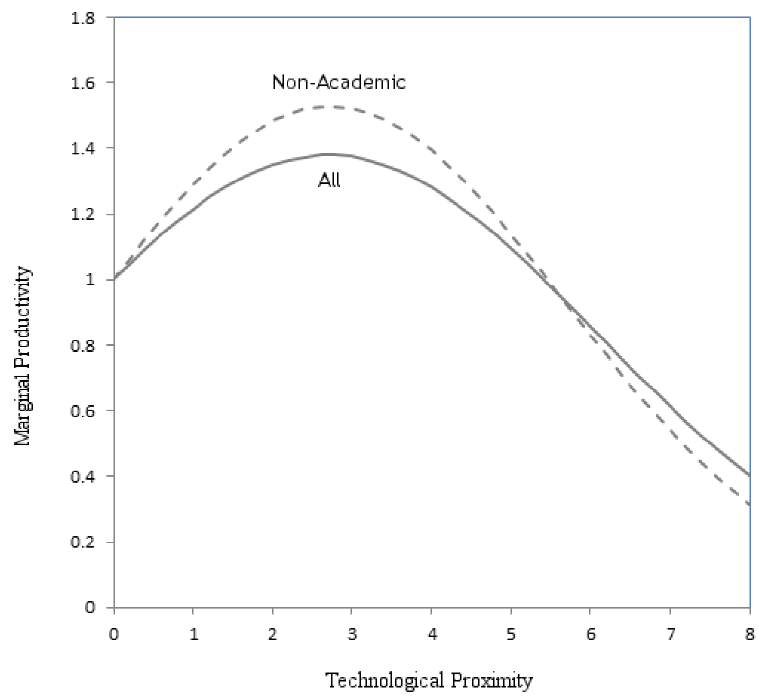

Figure 2: Marginal Effects of Technological Proximity on Collaborative Output