ETLA

ELINKEINOELÄMÄN TUTKIMUSLAITOS
THE RESEARCH INSTITUTE OF THE FINNISH ECONOMY
Lönnrotinkatu 4 B 00120 Helsinki Finland Tel. 358-9-609 900
Telefax 358-9-601 753 World Wide Web: http://www.etla.fi/

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Tuomo Nikulainen*

THE OUTCOMES OF INDIVIDUAL-LEVEL TECHNOLOGY TRANSFER AND THE ROLE OF RESEARCH COLLABORATION NETWORKS

* Etlatieto Ltd. / ETLA (The Research Institute of the Finnish Economy)

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Corresponding author: Tuomo Nikulainen, ETLA (The Research Institute of the Finnish Economy), Lönnrotinkatu 4 B, 00120 Helsinki, Finland. Phone: +358 50 548 1336. Fax: +358 9 601753. E-mail: tuomo.nikulainen@etla.fi

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ABSTRACT: This paper discusses the outcomes of university-industry interaction from the perspective of an individual academic researcher. Two contributions are made to the extant literature. First, in the existing research, the focus has mostly been on outcomes such as university-based patenting, licensing revenues, invention disclosures to technology transfer offices, and academic entrepreneurship. This narrow focus has excluded intangible outcomes, such as the identification of new research ideas and commercial opportunities, from the discussion. Therefore, in this paper, both intangible and tangible outcomes are taken into account, and the empirical analysis identifies unique individual-level factors related to the different types of outcomes. Second, in the extant literature, it is argued that a boundary-spanning position within different types of networks is related to higher performance and the identification of unique ideas. This aspect is analysed by identifying the role of a boundary-spanning position in research collaboration networks with respect to the different outcomes. The empirical results show that the different outcomes are clearly related to different individual-level factors, and that a boundary-spanning position in research collaboration networks is related to both intangible and tangible outcomes.

JEL Codes: O31, O33

Keywords: technology transfer, university-industry interaction, individual researchers, research collaboration, research networks, boundary spanning, nanotechnology

1. INTRODUCTION

The public research sector is part of national and regional innovation systems, in which public institutions are not only seen as pursuing knowledge but also as instruments of technological change in knowledge-based economies (Mowery and Sampat, 2004). The public research sector can be viewed as a strategic asset if the public sector's link to industry can be strengthened and technology transfer can be facilitated. The reason for the increasing importance of the public sector research relates to the private sector's incentives to engage in R&D that are below the social optimum due to the nature of knowledge as a public good and the technological uncertainty of new technologies (Arrow, 1962). For emerging science-based technologies, this is a particular problem, as smaller companies face challenges in accessing critical resources such as instrumentation and manpower, and larger companies are less keen on investing in technologies that are in an early and often uncertain stage of development. In this case, government-funded R&D undertaken in public institutions (universities and research institutes) plays an important role.

The role and importance of technology transfer have been widely addressed by policymakers. As a result, various reforms and programmes have been introduced to facilitate technology transfer. The most-cited examples of public initiatives are the Bayh-Dole Act and other legislative reforms enacted in the US during the 1980s and the European Framework Programmes in Europe, which aimed to enhance the collaboration between public and private sectors. Nowadays, most industrialised countries have introduced structures and initiatives to support technology transfer activities (Poyago-Theotoky et al., 2002; Siegel, 2007). In particular, the 'third' role of universities has been emphasised along with their more traditional activities in education and research. Universities are expected to engage with society to a greater degree than ever before, emphasising the importance of technology transfer as well as the commercialisation of science (Etzkowitz et al., 2000).

This broader engagement can be connected to the concept of the 'Mode 2' type of research, which is associated with more interdisciplinary and networked innovation systems, yielding more industry-relevant research than the traditional discipline-focused 'Mode 1' type of academic research (Gibbons et al., 1994; Foray and Gibbons, 1996; Mowery and Sampat, 2004). The importance of the 'Mode 2' type of research is viewed to be increasing in modern university-industry interaction and thus brings forth the increasing scale and diversity of knowledge inputs required in scientific research (Gibbons et al., 1994), which should be taken into account when discussing university-industry interaction and technology transfer.

The discussion of technology transfer has often focused on the national, regional or organisational levels, where aspects such as geographical proximity and the role of universities as a source of information have been addressed (for example Mansfield and Lee, 1996; Arundel and Geuna, 2004; Segarra-Blasco and Arauzo-Carod, 2008). In these studies, the unit of analysis has mostly been universities, companies, science parks, technology transfer offices, and academic spin-offs (for reviews, see Bozeman, 2000; Rothaermel et al., 2007; Siegel, 2007). In these discussions, the individual researcher's perspective has been often neglected, although it has gained some interest among scholars in recent years.

The extant literature on individual-level technology transfer has focused on explaining incentives for tangible outcomes such as academic entrepreneurship, patenting, licensing, and invention disclosures to university technology transfer offices (Agrawal and Henderson, 2000; Louis et al., 2001; Balconi and Laboranti, 2006; Bercovitz and Feldman, 2008; for reviews, see Rothaermel et al. 2007; Siegel, 2007). The first contribution of this paper is thus to broaden the perspective to other, more intangible outcomes, which have been only marginally addressed in existing research (Palmberg, 2008). In the current paper, different types of outcomes from interaction with companies ranging from tangible outcomes, such as receiving industry funding and patenting research results, to intangible outcomes, such as identifying new research ideas and commercial opportunities, are taken into account.

The second contribution of this paper to the extant literature is to establish a connection between the outcomes of university-industry interaction and boundary spanning in research collaboration networks. The inclusion of this aspect incorporates the concept of the ‘Mode 2’ type of research into the discussion of university-industry interaction. A large body of the extant literature on networks has focused on network characteristics and actors’ position in them, which have often been linked to a variety of performance indicators at both the firm level (for example, Walker et al., 1997; Rosenkopf and Nerkar, 2001) and the individual level (for example Nicolaou and Birley, 2003; Burt, 2004; Cross and Cummings, 2004; Nerkar and Paruchuri, 2005; Cantner and Graf, 2006). In these studies, particular attention has been given to the role of boundary-spanning positions in networks, where a central position within a network enables the control of knowledge flows between different parts of a network. Although the empirical findings are not conclusive, from an individual-level perspective, it has been found that a boundary-spanning position is associated with higher performance, which has been connected, for example, to higher salaries, promotions and creativity (Burt, 1992 and 2004; Seidel et al. 2000; Mehra et al. 2001; Cross and Cummings, 2004). Based on these empirical findings, the current paper aims to identify the degree to which a boundary-spanning position in research collaboration networks is related to different types of outcomes from university-industry interaction, as suggested by the literature on the ‘Mode 2’ type of research (Gibbons et al., 1994; Foray and Gibbons, 1996; Mowery and Sampat, 2004).

The context for the study is the university-based nanotechnology-related community in Finland. Nanotechnology is an example of a science-based field, where commercial expectations are high, and the underlying technologies and sciences are seen as potentially developing into a general purpose technology (Lipsey et al., 2005; Youtie et al., 2008). Nanotechnology is also viewed to be a very interdisciplinary field (Schummer, 2004; Miyazaki and Islam, 2007) where ‘Mode 2’ type of research might be even more relevant when compared to other emerging technologies such as biotechnology. Despite these very high expectations, which may be partially hyped, nanotechnology is still in an early stage of development, and there are several directions for commercialisation, highlighting the need to understand the facilitating and hindering factors of technology transfer also from an individual researcher perspective.

The paper is structured as follows. Section 2 provides an analytical framework for the paper by discussing relevant contributions in the existing literature on university-industry interaction and boundary spanning in research collaboration networks. Section 3 discusses the data and addresses methodological questions. Section 4 presents the empirical analysis. Finally, Section 5 discusses the results and draws conclusions.

2. ANALYTICAL FRAMEWORK

When new science-based technological fields emerge, the transfer of scientific research towards more applied research or even commercialised products and processes requires the involvement of several different actors. Universities, research institutes, government agencies and industry all play an important role in the process of technology transfer. The literature describing the interaction between different actors has seen a rapid growth in recent decades ranging from more theoretical and conceptual works to empirical research (for reviews, see Bozeman, 2000; Rothaermel et al. 2007; Siegel, 2007).

In the discussion of technology transfer from a theoretical point of view, the definition of technology is often debated (Bozeman, 2000; Dosi and Nelson, 2010). For example, Bozeman (2000) argues that defining the concept of technology transfer is difficult, as 'technology' might be understood in many ways, and describes how 'knowledge' is different from technology. Therefore, technology transfer can be seen as a part of a broader context of knowledge creation and knowledge transfer (Gibbons et al., 1994). In this paper, the focus is mainly on the transfer dimension, particularly in the context of the university-industry interaction; this paper also incorporates some elements of knowledge creation through the discussion of the role of research collaboration networks as a factor related to the different types of outcomes from university-industry interaction.

2.1. University-industry interaction and outcomes from an individual researcher perspective

In the extant literature, there is a small but increasing number of contributions that focus on the university-industry interaction from an individual researcher's perspective (Agrawal and Henderson, 2000; Louis et al., 2001; Brennenraedts et al., 2006; Balconi and Laboranti, 2006; D'Este and Patel, 2007; D'Este and Perkmann, 2007; Palmberg, 2008; Perkmann and Walsh, 2009; Boardman and Ponomariov, 2009; Perkmann, 2009). The most prevailing research direction in these discussions has focused on the determinants of different types of interactions between university researchers and companies. The aim in these studies was to understand the significance of different modes of industry interaction and to identify what kinds of individual characteristics are related to different types of interactions. The discussed interactions range from more informal modes, such as conferences, to more formal modes, such as contract research. In these studies, factors such as researcher's scientific and professional background, motivations and age are identified as having a connection with the different modes of interaction.

Whereas there has been increasing interest on the different modes of interaction between university researchers and companies, the outcomes of this interaction from an individual perspective have received only very limited interest. As mentioned, the focus in the extant literature on outcomes related to technology transfer has mostly been on the established tangible outcome indicators such as patents, licensing, invention disclosures to university technology transfer offices and academic entrepreneurship (Rothaermel et al. 2007; Siegel, 2007).

An exception in the literature is Palmberg (2008), who analyses both the intangible and tangible outcomes on the university-industry interaction and identifies significant differences between university and company researchers. He takes into account the different modes of interaction and perceived challenges in university-industry interaction, identifying a dominance of idea generation over the patenting and licensing of research results. In the current paper, the focus is solely on the university researchers, allowing for a more detailed analysis and inclusion of the research collaboration network dimension.

Based on the extant research on the university-industry interaction and the related outcomes, it is evident that the outcomes are related to several individual-level factors. In this paper, the focus is on the researcher’s age, academic productivity (publications), educational and professional background, motivations for research and challenges experienced in technology transfer. As the literature has already provided empirical evidence that these factors are related to the different types of outcomes, in the current paper, they are taken into account and are treated as ‘controls’. This enables the identification of the connection between the different types of outcomes and the boundary-spanning roles of researchers in research collaboration networks. This provides insights into the individual researcher’s ability to collaborate across organisational and academic discipline boundaries through research collaboration. Although the individual factors are viewed as controls, it is worthwhile to review some of the empirical literature that reveals their importance in university-industry interaction.

The researcher’s age is often mentioned in the literature as having an impact on the researcher’s activity in technology transfer. It has been found to have a positive connection with the interaction with industry (Bozeman and Gaughan, 2007; D'Este and Patel, 2007; D’Este and Perkmann, 2007 and 2009). Senior researchers have had more opportunities to interact with the companies than their younger peers, but there is a possibility that the senior faculty is more locked in the academic ‘ivory tower’, where broader engagement with society is potentially regarded less positively.

There is also empirical evidence that links between university researchers and industry has a positive connection with scientific productivity (Balconi and Laboranti, 2006). In addition, it is found that some individual researchers represent a locus of productivity and interaction with industry, and for this reason, these individuals are sometimes referred to as ‘star-scientists’ (Zucker and Darby, 2001). A typical characteristic of a ‘star-scientist’ is a high publication rate, suggesting that high academic productivity relates to more frequent industry interaction.

Another aspect that needs to be addressed relates to the context of this study. The degree to which the current research topic of the researcher is nanotechnology-orientated should be taken into account, as there might be some technology specific aspects due to this focused context. Nikulainen and Palmberg (2010) note that nanotechnology seems to differ in some dimensions of technology transfer, such as educational background, motivation for research, and challenges related to the basic research orientation. These findings highlight that the technological context and its potential specificities should be controlled for.

The most frequently mentioned factor related to individual-level technology transfer is the educational background or the affiliation of a researcher. There is significant body of empirical evidence that different scientific disciplines interact with companies through a variety of ways and with different intensities (Schartinger et al., 2002; D'Este and Patel, 2007; Landry et al., 2007; Palmberg, 2008). The underlying reason for this is that researchers working in academic disciplines that are more applied are inclined to interact more frequently and intensely with companies than those from some of the more theoretical disciplines; an example of this difference is that between applied chemical engineering and theoretical physics. In addition to educational background, the professional experience is important to consider, as industry experience most likely not only facilitates technology transfer but potentially directs the research topics towards research questions that are more relevant for industry (Dietz and Bozeman, 2005).

In the process of transferring scientific knowledge to industry, university researchers experience different types of challenges that may relate to the outcomes of the university-industry interaction (Bozeman, 2000; Schartinger et al., 2001; Palmberg, 2008; Nikulainen and Palmberg, 2010). In particular, Palmberg (2008) provides interesting insights to the challenges between academia and industry by identifying that academic researchers view their basic research orientation and the identification of commercial opportunities as key challenges when transferring scientific knowledge to industry.

Motivational aspects are also identified to matter in university-industry interaction. D'Este and Patel (2007) discuss the drivers of interaction with industry among university researchers, highlighting the critical role of commercial motivations as a contributing factor in technology transfer. The main drivers for initiating research or development activities in a specific field are quite commonly recognised factors that relate to technology transfer (Bozeman, 2000; Schartinger et al., 2001; Nikulainen and Palmberg, 2010).

Based on the literature discussed above, it is evident that the university researchers involved in university-industry interaction have a variety of characteristics that should be taken into account. Interestingly, one aspect that has been left outside the scope of research in the extant literature is the role of research collaboration networks with respect to the university-industry interaction.

2.2. Role of boundary spanning in research collaboration networks

Collaborative networks among university researchers have been found to have a positive connection with publication and patent productivity, suggesting that the role of these networks should not be underestimated (Landry et al., 1996). Therefore, it is interesting to observe that in the extant literature on university-industry interaction, this aspect has not been accounted for. The ability to utilise these networks may prove advantageous in creating more industry-relevant scientific knowledge by combining new ideas in an interdisciplinary environment, as suggested by the literature on the 'Mode 2' type of research (Gibbons et al., 1994; Foray and Gibbons, 1996; Mowery and Sampat, 2004). The 'Mode 2' type of knowledge creation emphasises the context specificity of research potentially undertaken in a more interdisciplinary environment when compared to the 'Mode 1' type of research, which is regarded as being more traditional academic research and as often being investigator-initiated, discipline-based and discipline-bound knowledge production.

When discussing the role of research collaboration networks in technology transfer, it is necessary to address some of the relevant concepts used in the literature of network analysis. The analysis of networks focuses on different actors, for example, individuals, companies, and organisations, and their interdependency in networks formed based on different types of connections or ties, for example, verbal communication between individuals, alliances between companies, or, as in this paper, co-authorship in scientific academic publications and co-inventorship in patents. All of these interdependencies can be illustrated as networks, where the shape of a network determines the network's usefulness to actors within the network. Smaller, and potentially isolated, network can be less useful to their members than more open network with many ties and connections (Scott, 1991). This fragmentation leads to a situation where networks with plenty of connections to actors outside the main network are more likely to introduce new ideas and opportunities when compared to closed networks with fewer ties. With respect to the current paper, the most important finding is that actors can act as brokers within their networks by bridging two parts of the network that are not otherwise directly connected (Scott, 1991). A gap in a network is often referred to as a structural hole, which is defined as a lack of connections between different actors in a network (Burt, 1992). In other words, there are no connecting ties between different subgroups within the network. By filling a structural hole, an individual is placed in a brokerage position, where one is able to control the flow of information between the different parts of the network. The brokers between the different parts of the network are often viewed to hold a boundary-spanning position (Rosenkopf and Nerkar, 2001; Cross and Cummings, 2004).

To measure whether an individual researcher has a boundary-spanning position in research collaboration network, a statistical measure is employed relating to the centrality of an individual in a network. The statistical centrality measures how connected the individual researcher is to other researchers in the network. The betweenness centrality (for a definition, see Freeman, 1979) provides an indication of the extent to which an actor lies between different parts of the network and the extent to which this actor is potentially filling a structural hole. The empirical literature indicates that high betweenness centrality is associated with higher performance and creativity at an individual level (Burt, 1992; 1997; 2004; Seidel et al. 2000; Mehra et al. 2001; Cross and Cummings, 2004).

A boundary-spanning position allows one not only to control and facilitate knowledge flows but also to block them (Hauschildt and Kirchmann, 2001). Therefore, a boundary-spanning position can be associated with positive and negative aspects of knowledge flows. In the current paper, it is assumed that the ability to control and access knowledge flows entails a positive connection rather than the negative blocking effect on technology transfer.

2.3. Context

In this paper, the outcomes of university-industry interaction at the individual level and the boundary-spanning position in research collaboration networks are analysed in the context of a new emerging technological field. Nanotechnology has been hailed as a new revolutionary technology building on advances in a variety of scientific disciplines and is often viewed as a very multidisciplinary and interdisciplinary field (Schummer, 2004; Shea, 2005; Hullman, 2006; Lipsey et al., 2005; Bozeman et al., 2007; Meyer, 2007; Youtie et al., 2008; Nikulainen and Palmberg, 2010). The validity of these radical statements of the disruptive nature of nanotechnology can only be answered in the future, as at the moment, most the nanotechnology-related research efforts are more basic research orientated (Miyazaki and Islam, 2007). This emerging technology was chosen to be the context of this paper, as nanotechnology has some unique characteristics; most notably, it is viewed as being multidisciplinary and interdisciplinary (Meyer, 2007). The ability to combine research efforts across different areas related to nanotechnology is a potential source for creating very relevant applications for a variety of industries and potentially leading to more radical technological advances, as implied by the 'Mode 2' type of research.

Public interest in nanotechnology has increased tremendously in the last few years, leading to a surge of public investment in nanotechnology (Palmberg and Nikulainen, 2006). The interest in this new science-based technology is mostly based on advances in science and technology, but there is a general concern that some of the beliefs associated with nanotechnology are built more on hype than actual potential. Similar enthusiasm has been observed in the field of biotechnology, where initial expectations were met with major breakthroughs in only some areas of life sciences (Hopkins et al., 2007). This paper does not aim to contribute to the discussion of the potential future role of nanotechnology in society but focuses on understanding the relationship between the outcomes of university-industry interaction and individual factors when nanotechnology-related scientific knowledge is transferred to the use of industry.

The context for this study is the university-based nanotechnology-related community in Finland. Technology transfer is one of the core elements of Finnish innovation policy, which is implemented through a variety of policy initiatives aiming to facilitate the interaction between universities and companies (Ylä-Anttila and Palmberg, 2007). Policymakers in Finland have substantially promoted the development of nanotechnology and related sciences (an approximate total of 100 million euros by the end of 2010), which is a relatively high investment even in international comparison (Palmberg and Nikulainen, 2006). This large public interest towards nanotechnology in Finland is partially based on commercial expectations, but it is also based on the strong scientific nanotechnology-related knowledge base in Finland. Finland is comparably strong in this field when publication activity is considered, while it seems that more applied research, measured through patents, is lagging compared to that of other countries (Palmberg and Nikulainen, 2006; OECD, 2009). The statistical indicators clearly show that nanotechnology is still very science-based, highlighting the importance of understanding the mechanisms through which academic research is transferred to the private sector. Moreover, Finnish nanotechnology research community is still in its infancy, like in many other countries, and the underlying research collaboration networks are still forming. In a similar fashion, the number of companies involved in nanotechnology-related activities has been reported to have increased significantly in Finland in recent years. The number of Finnish companies with either nanotechnology-related activities, or a strategic plan to use it, has been suggested to be around 200 (Spinverse Consulting, 2008). This figure seems quite high, and in other instances, the number of companies with potential links to nanotechnology has been identified as being much smaller (Nikulainen, 2007). Based on these findings, it could be argued that the large-scale application of nanotechnology in different industries has yet to be witnessed.

3. DATA AND METHODOLOGY

The relationship between the different outcomes of university-industry interaction and the various individual-level characteristics is analysed using three different data sets. The main data source for the outcomes and the individual-level factors is a survey that focuses on various aspects related to technology transfer. The two other data sets are based on patent and publication data and are used to identify the boundary-spanning position of individual researchers in patent and publication networks, which are viewed as representing research collaboration networks.

3.1. Identifying the Finnish academic nano-community

The first data set used in this paper is based on a survey that aimed to identify the knowledge base, experiences, and motivations in technology transfer among academic researchers active in the field of nanotechnology in Finland. The survey population was identified from patent and publication data through a nanotechnology keyword-search algorithm developed by FhG-ISI in Germany. The keyword search was used to identify nanotechnology-related patents and peerreviewed journal articles (published in ISI SCI-Index) before January 2006. The affiliation of these patents and publications to Finland was established based on the criterion that at least one of the researchers or inventors had a Finnish affiliation (for the keyword search algorithm, see Noyons et al., 2003; Palmberg and Nikulainen, 2006).

The intensity of involvement in nanotechnology-related research varied within the identified population. This is reflected in the distribution of publications and patents, which is highly left-skewed with many authors having only 1 publication related to nanotechnology. To keep the focus on the more nanotechnology-orientated researchers, a threshold of having at least three publications was applied. For patents no threshold was applied with at least one patent publication being considered sufficient. Based on this procedure, 592 academic researchers were identified. A web-based survey was sent out during September–November 2006 with two reminders (more details on the survey and related practicalities can be found in Palmberg et al., 2007). Out of the 592 identified university researchers, 386 researchers answered, corresponding to a response rate of 65.2%.

3.2. Outcomes of university-industry interactions and related individual-level factors

The dependent variables are based on a survey question asking how often the researchers have achieved various outcomes when interacting with companies. Based on this question, four dependent variables are formed. The two intangible outcomes identified to what degree the researcher has *i) identified new research questions* and *ii) recognised commercial opportunities*. The tangible outcomes indicate to what extent the researcher has *iii) received funding from industry* and to what extent *iv) patenting of research results* has occurred as a consequence of industry interaction.

In an ideal situation, dyadic pairs of academic researchers and companies would have been created, where both parties evaluate the contribution of the researcher, allowing for a more objective interpretation of the outcomes. Unfortunately, this possibility is not available, as the researchers have interacted with a variety of different companies; therefore, establishing dyadic pairs is beyond the scope of this research.

The summary statistics of all variables, which will be used in the regression analysis, are presented in Table 1. Most of the questions asked had response categories on a scale from 1 to 4, where a variable value of 1 equals 'not important' or 'not at all' and a value of 4 equals 'very important' or 'very much'. The number of publications was asked on a categorical scale, where a low value equals a low number of publications. The questions related to educational and professional backgrounds are represented through binary variables, where a value of 1 equals a positive answer. The age of the respondent is a continuous variable, as are the betweenness centrality measures (approximating the boundary-spanning position). The latter are also standardised to facilitate the interpretation of the regression results. It should also be noted that for a few of the respondents, there were some missing values, and in order to have a consistent number of observations the overall mean for the question was used to replace the missing value. The summary statistics are shown in Table 1.

Table 1. Summary statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Outcomes					
Identification of ideas	386	2.085	0.989	1	4
Ident. of commercial opportunities	386	1.826	0.899	1	4
Funding	386	2.078	1.027	1	4
Patenting	386	2.187	0.915	1	4
Controls					
Age	386	44.576	11.209	26	70
Publications	386	4.172	1.488	1	6
Nano-intensity	386	2.656	1.161	1	4
Background					
Physics	386	0.322	0.468	0	1
Chemistry	386	0.255	0.437	0	1
Biological/Medical	386	0.307	0.462	0	1
Multiple degrees	386	0.075	0.263	0	1
Industry experience	386	0.241	0.428	0	1
Challenges					
Passive researchers	386	1.385	0.710	1	4
Basic research orientation	386	2.521	1.135	1	4
Identifying commercial applications	386	2.149	0.985	1	4
Communication problems	386	1.682	0.809	1	4
Ownership issues	386	1.697	0.846	1	4
Lack of business skills	386	2.028	0.971	1	4
Lack of production technologies	386	1.818	0.918	1	4
Motivations					
Own interest	386	3.738	0.594	1	4
Supervisor interest	386	2.344	1.118	1	4
Public funding	386	2.636	0.933	1	4
New instrumentation	386	2.482	1.008	1	4
Visit abroad	386	2.223	1.000	1	4
Commercial potential	386	1.992	0.977	1	4
Centrality					
Publication betweenness	386	0	1	-0.191	15.800
Patent betweenness	386	0	1	-0.066	19.386

In the following, some of the key insights from the summary statistics of the independent variables are highlighted, as they may have an impact on the interpretation of the statistical findings. First, a distinction was also made between researchers more intensively involved in nanotechnology-related research areas and those whose research is related to a lesser degree to nanotechnology. The definition of nanotechnology used in this paper comes from the U.S. National Nanotechnology Initiative (NNI). The definition of the NNI is as follows: *"Nanotechnology is the understanding and control of matter at dimensions of roughly 1 to 100 nanometres, where unique phenomena enable novel applications. Encompassing nanoscale science, engineering and technology, nanotechnology involves imaging, measuring, modelling, and manipulating matter at this length scale."* The results on the nanotechnology intensity suggest that the sample consists of researchers involved to varying degrees in nanotechnology-related research (an average value of 2.7 out of maximum of 4), suggesting that it is useful to take into account any technology specificities arising from the object of potential transfer (Palmberg et al., 2007; Nikulainen and Palmberg, 2010).

Second, the descriptive statistics also provide interesting insight into the educational and professional backgrounds of the researchers. The binary educational variables show that the most common background is physics (32.2% of all respondents), followed by chemistry (25.5%) and biological/medical (30.7%) backgrounds. In addition, 7.5% of the researchers have more than one degree. This diversity of educational backgrounds should be taken into account, as different disciplines do interact with industry to varying degrees (Schartinger et al., 2002). Having industry experience is fairly common in the academic nano-community, as 24.1% of the respondents have at least one year of work experience in industry.

The different challenges experienced in technology transfer are related to the passiveness of researchers, the basic research orientation of the current projects, the identification of new research questions or product ideas, communication problems between university researchers and companies, challenges in determining the ownership of property rights, a lack of business skills among researchers, and a lack of production of technologies. The descriptive results indicate that the basic research orientation, the identification of new research questions or product ideas, and the lack of business skills are viewed to be the most significant challenges in technology transfer. It is argued that those individuals reporting higher levels of challenges in co-operation might be less inclined to interact with companies and achieve outcomes (Palmberg, 2008).

The reasons for engaging in the current research activities will most likely affect a researcher's participation in industry interaction (D'Este and Patel, 2007). The motivations identified in this paper are the researcher's own interest in the topic, supervisor-imposed interest, the availability of public funding, the availability of new research instrumentation, a visit to a foreign university or research institute, and the commercial potential of the research topic. The researcher's own interest in the research topic is the most significant motivation. The other motivations are also seen as significant, particularly the availability of public funding, whereas the commercial potential of the research topic is found to be a less significant motivation.

3.3. Research collaboration networks

The most important independent variables relate to the boundary-spanning position, which is approximated through the betweenness centrality in patent and publication networks. The data sets used to create the research collaboration networks were collected from two different sources for the period 2000-2005 in order to focus more on the recent activities of the researchers.

The nanotechnology patents were collected from Questel-online based on the identification process using the earlier-mentioned keyword search algorithm (FhG-ISI). From this data set of patents, a collaborative network was built, where the connection between researchers was established based on co-inventorship in a patent publication. To make the patent network more realistic, the original data sets were expanded to include not only nanotechnology-related patents but also all other patents of the identified academic researchers. After collecting this data, the network was expanded even further by collecting all patents of the co-inventors of the original patenting population. This provided a more extensive picture of the collaborative networks related to the academic nanotechnology community in Finland, as the focus is not only on the nanotechnology-related activities but also on the other activities of these individuals. Based on this procedure, a patent network of 1 289 individuals was created.

The publication data (from ISI SCI-Index) for creating a second collaborative network was collected by using another algorithm designed to identify nano-related publications (Zitt and Bassecoulard, 2006). In a similar fashion as with the patents, all the other publications of the authors and their co-authors were collected in order to have a more extensive view of their academic collaboration. Through this procedure, a publication network of 20 077 individuals was created.

Both of the obtained networks are fragmented. Only few subgroups of the network are connected, indicating that the academic nanotechnology community mostly consists of isolated research groups. The fragmented structure of both networks is highlighted by the low density in both the publication and patent networks. The density is the proportion of connections in a network relative to the total number possible ones. A value of one for density would imply a network in which all actors are connected to each other, whereas a value of zero would indicate that none of the actors in the network is connected. The densities are 0.00010 for the publication network and 0.00155 for the patent network. The high fragmentation supports the argument that nanotechnology is not a single technology but rather a set of technologies only marginally connected to each other.

There are some relevant methodological aspects affecting the analysis that need to be addressed. The most notable one relates to the discussion on network analysis and collaborative networks. Katz and Martin (1997) discuss research collaboration at length, concluding that the usual measures of research collaboration (for example, joint publications) only refer to certain types of collaboration, failing to take into account the diversity of academic interactions. However, when analysing large datasets of academic researchers, finding an objective and efficient method for establishing connections between individual researchers is difficult. Therefore, the focus in this paper is on joint publication and patenting activity, as this approach allows establishing networks based on research collaboration both in basic research (publications) and in more applied research (patents).

Regarding the networks, it should be noted that networks based on joint patenting activities indicate codified co-operation between the individuals. Although the patenting practices and ownership aspects differ between organisations, the inventors are usually credited for their work by indicating the inventors of the inventions. For publications, the co-authorship practices are slightly different. Sometimes the list of authors does not correspond to the actual work conducted and is more of a list of contributors. This is particularly relevant in the case of physics, where some papers have several hundred authors (Newman, 2001). Therefore, in this study, a limit was set for the maximum number of authors allowed in a paper that can be seen to actually have interacted with each other. The limit was set to 18 authors, as papers with more authors usually have at least several dozen authors, and publications with more than 18 authors were thus excluded from the sample. This resulted in the exclusion of 2% of the papers. This was necessary, as including the papers with several hundred authors would have created links between researchers who most likely have no real-world connections to one another and therefore cannot be seen as being part of the research collaboration network of a specific researcher.

The betweenness values are standardised to make differences between researchers more clear. By looking at the standardised minimum and maximum values of the centrality measure (Table 1), it is clear that they vary greatly and that the underlying distribution is highly skewed with a high number of researchers displaying a low centrality value. This indicates that only a few researchers are well connected in these collaborative networks. When the centrality measures were matched to survey data, the publication network matched with all of the 386 respondents, whereas the patent network matched with only 58 respondents. The low number of identified inventors in the patent network compared to researchers in the publication network corresponds with the expectations that academics are more focused on publishing research results than on patenting them (Dasgupta and David, 1994; Stephan, 1996). The remaining unmatched non-patenting survey respondents received a value of 0 before being standardised, which allows using all the available observations in the following regression analysis.

4. STATISTICAL ANALYSIS

The purpose of the following analysis is to identify the factors that are related to the different types of outcomes of university-industry interaction. As there are four different dependent variables (identification of research questions, identification of commercial opportunities, receiving industry funding, and patenting of research results), all of them need to be addressed individually. Each of the dependent variables is first related to the factors identified in the existing literature as having a connection with the outcomes. These factors can be also seen as control variables for the betweenness variables, which aim to address the role of boundary-spanning in research collaboration networks with respect to the different types of outcomes. The regression results are presented in Table 2.

Table 2. Estimation results for the different outcomes (ordered logistic regression with robust standard errors)

Type of outcome	**INTANGIBLE**				**TANGIBLE**			
Dependent variable / Outcome	***New research ideas***		***Commercial opportunities***		***Funding***		***Patenting***	
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
Centrality								
Publication betweenness		0.037		0.121***		0.088**		0.172**
Patent betweenness		0.049		-0.170**		2.521+		-0.002
Background								
Age	-0.013	-0.012	-0.023+	-0.023+	-0.004	-0.004	-0.015	-0.015
Publications	0.187*	0.180*	0.257**	0.250**	0.294**	0.271**	0.509***	0.493***
Nano-intensity	-0.215*	-0.208*	-0.224*	-0.240*	-0.119	-0.109	-0.007	-0.005
Physics	-0.505+	-0.504+	-0.336	-0.383	-1.258***	-1.265***	-0.868***	-0.906***
Chemistry	0.120	0.115	0.267	0.300	-0.071	-0.141	0.736**	0.750**
Biological/Medical	-1.325***	-1.309***	-0.492+	-0.537+	-1.801***	-1.781***	-0.669*	-0.682*
Multiple degrees	-0.018	-0.076	0.052	0.177	0.171	0.052	0.115	0.134
Industry experience	0.545**	0.548**	0.508*	0.505*	0.689***	0.649**	0.571**	0.580**
Challenges								
Passive researchers	-0.422**	-0.425**	-0.320+	-0.347+	-0.244+	-0.247+	-0.187	-0.205
Basic research orientation	-0.359***	-0.356***	-0.348***	-0.360***	-0.372***	-0.356***	-0.483***	-0.491***
Identifying com. appl.	0.177	0.177	0.101	0.115	0.098	0.093	0.325**	0.335**
Communication problems	0.010	-0.007	0.210	0.210	-0.026	-0.050	-0.006	-0.028
Ownership issues	0.333**	0.336**	0.343**	0.346**	0.442***	0.454***	0.321**	0.331**
Lack of business skills	-0.044	-0.040	-0.102	-0.094	-0.032	-0.012	0.046	0.060
Lack of production tech.	0.213+	0.211+	0.120	0.110	-0.01	-0.009	0.048	0.038
Motivations								
Own interest	0.029	0.024	-0.144	-0.134	0.088	0.058	-0.442*	-0.433*
Supervisor interest	-0.092	-0.096	-0.118	-0.141	-0.031	-0.041	-0.178+	-0.201*
Public funding	-0.096	-0.091	0.020	0.032	-0.018	-0.003	0.135	0.154
New instrumentation	0.383***	0.375***	0.275**	0.262**	0.212*	0.209*	-0.059	-0.080
Visit abroad	0.107	0.110	0.087	0.095	0.015	0.039	0.112	0.122
Commercial potential	0.542***	0.552***	0.862***	0.868***	0.489***	0.519***	0.530***	0.547***
Summary statistics								
# of observations	386	386	386	386	386	386	386	386
Wald test	144.12***	228.47***	158.96***	158.35***	142.06***	140.11***	149.98***	157.01***
Pseudo R-squared	0.158	0.159	0.181	0.186	0.169	0.179	0.198	0.201

+ p<0.15, * p<0.10, ** p<0.05, *** p<0.01

The statistical validity and the robustness of the results are addressed through several approaches. First, the Wald test suggests that the models have a good overall fit. Second, the estimations use robust standard errors. Third, the analysis of marginal effects additionally indicates that the results are robust. The marginal effects also relate to the parallel regression assumption, stating that the relationships between each pair of outcome groups are identical. This assumption was also separately tested, showing that it is not violated. Third, all of the regressions are also estimated with the ordered probit model yielding very similar results, as only few of the explanatory variables had a slightly lower significance level. Finally, in Appendix I, the correlation matrix is presented and indicates that multicollinearity does not affect the estimation results or their interpretation.

5. DISCUSSION AND CONCLUSIONS

5.1. Findings from the statistical analysis

Looking first at the results on the role of a boundary-spanning position with respect to the different dependent variables provides interesting insights. The first estimations indicate that when addressing the outcome related to the identification of new research ideas, no evidence was found that a boundary-spanning role in either network has a connection with the identification of new research ideas. It may be that in the interaction between university researchers and companies, the identification of research ideas is discipline focused and interdisciplinary factors play a marginal role.

The second dependent variable measured the how often the researcher identified commercial opportunities when interacting with companies. The ability to span boundaries is strongly connected to this outcome. Boundary spanning in publication networks has a positive connection with the identification of commercial opportunities, whereas a similar position in patent networks has a negative connection. This result may indicate that the ability to combine different areas of basic research is related to the identification of commercial potential. The finding related to the boundary-spanning role in the patent networks suggests that focusing on a specific area of applied research is relevant in identifying commercial opportunities.

When looking at the role of boundary spanning in achieving funding from the private sector, the estimation results provide interesting results. The connection with industry funding and publication network is positive, but the strength of the connection is fairly weak. For the patent network, the results are marginally positive ($p<0.15$), but the size of the connection is surprisingly strong. These results suggest that the boundary-spanning position in both networks matters in achieving industry funding. The result for the patent network suggests that the ability to span organisational and academic discipline boundaries in more applied research is very relevant for attracting industry funding. The boundary-spanning position in the more basic research-related publication network seems to matter less, suggesting that interdisciplinary basic research may be less relevant in attracting industry funding.

The final dependent variable is related to the patenting activity resulting from industry interaction. It is positively connected to boundary spanning in publication networks, suggesting, as with the identification of commercial opportunities, that the ability to combine different areas of basic research is related to achieving patenting as a result of university-industry interaction. For patent networks no statistical connection was found.

The findings related to the boundary-spanning position in research collaboration networks with respect to different types of outcomes suggest that there is a connection between the variables. Boundary spanning in the publication networks has a statistically significant positive role in identifying commercial opportunities, receiving industry funding and patenting. There is some evidence that a similar position within patent networks has a negative connection at least with identifying commercial opportunities, although with industry funding, the connection is positive; as a result, clear conclusions of the role of boundary spanning in patent networks related to applied research is hard to draw.

These findings confirm to some extent that a boundary-spanning position in social networks does have a role in the performance of an individual. Interestingly, both positive and negative connections were found, which differs from earlier findings, where only a positive connection was established (for example, Seidel et al. 2000; Mehra et al. 2001; Cross and Cummings, 2004). The difference in the results most likely derives from the context of the studies and also from the different types of networks studies, as many of the existing studies focus on intra-organisational communication patterns.

As an interesting side note, it should be mentioned that the empirical findings from the regressions and correlation matrix (Appendix I) provide a new insight in the extant literature. It has been found that high scientific productivity, in the form of publications, is linked with high patenting activity (for example, Zucker and Darby, 2001; Breschi et al., 2007). While this aspect was not directly addressed in the current paper, the results suggest that a boundary-spanning position in one's publication network does not automatically relate to a similar position in a patent network. This suggests that interdisciplinary basic research may not relate to interdisciplinary inventions. This is something that would require more exploration, which is unfortunately beyond the scope of the current paper.

The empirical findings on the role of boundary spanning can be also reflected in the discussion of the role of the 'Mode 2' type of research in modern university-industry interaction (Gibbons et al., 1994; Mowery and Sampat, 2004). While the estimation results support the argumentation that interdisciplinary research is becoming ever more important in the university-industry interaction, the connection with the outcomes is fairly small, suggesting that it should be taken into account when discussing modern university-industry interaction, but it is not the most critical factor in achieving the outcomes in university-industry interaction. For this reason, it is also worthwhile to discuss the key findings for the control variables and whether they produce similar results as identified in the existing literature.

The age of the researcher fails to have any substantial statistical significance, while in the literature, this has been identified as having a particular connection to tangible outcomes such as patenting (Bozeman and Gaughan, 2007; D'Este and Patel, 2007). Publication activity is positively connected to the outcomes, as suggested in the extant literature (Balconi and Laboranti, 2006; Zucker and Darby, 2001). The connection is strongest with the tangible outcomes, but it also has a significant role in intangible outcomes.

Interestingly, nanotechnology intensity has a negative connection with intangible outcomes. This is a similar finding to earlier contributions on the role of nanotechnology in technology transfer (Nikulainen and Palmberg, 2010), where the basic research nature of nanotechnology-related activities has a negative connection to technology transfer, potentially resulting in a lack of industry interest on nanotechnology.

Educational and professional background based on the estimations clearly has a connection to the outcomes. The industry experience has a strong positive connection to all outcomes as suggested in the literature (Dietz and Bozeman, 2005). An educational background in physics and in biological/medical sciences is in most of the estimations negatively connected to achieving outcomes. In particular, the tangible outcomes are negatively connected, whereas those with backgrounds in chemistry might be working in more applied research areas, resulting in tangible outcomes such as industry funding and patenting. These findings are similar to those in the literature (Schartinger et al., 2002; D'Este and Patel, 2007; Landry et al., 2007; Palmberg, 2008).

The estimation results for those experiencing challenges in the context of interacting with industry indicate that the passiveness of university researchers and their basic research orientation is negatively connected to the outcomes. In other words, those researchers experiencing these types of challenges are less likely to achieve outcomes from industry interaction. On the other hand, those researchers that see ownership issues as a challenge are more likely to achieve these outcomes. Interestingly, the challenges experienced in identifying commercial applications are positively connected to the patenting outcome. These findings are similar to those of an earlier study (Palmberg, 2008), where it is suggested that this result comes from the research orientation of researcher's being orientated to either basic or more applied research, even when controlling for the researcher's academic field.

Looking at the relationship between motivations and outcomes, it is clear that the most statistically significant factor is the commercial motivation, as argued in the extant literature (D'Este and Patel, 2007). Also, the availability of new research instrumentation also has a strong connection with the intangible outcomes. Interestingly, the patenting outcome is negatively related to one's own research interest as well as supervisor-imposed motivations, suggesting that industry's needs are taken into account when entering a specific research area.

5.2. Implications and future research

This paper assesses the role of boundary spanning and interdisciplinary research in achieving various outcomes from university-industry interaction. The factors identified in the existing literature as having a connection with the outcomes were also taken into account to isolate the role of boundary spanning in research collaboration networks.

The empirical results suggest that the ability to combine different research areas has a positive connection with the outcomes of university-industry interaction. The positive connection was established with the identification of commercial opportunities, receiving industry funding as well as patenting. It should be noted that this connection relates to the research collaboration in publication networks. As the publication networks are reflecting the basic research activities in different scientific fields, it can be said that interdisciplinarity in academic research relates to higher levels of outcomes. Although the statistical estimations provide evidence of a connection between boundary spanning and the different outcomes, the significance to other factors related to the outcomes is far greater. This should be kept in mind when interpreting the results.

The results of the paper provide some implications for future research. The findings in the current paper indicate that the role of research collaboration networks should not be underestimated, as suggested by Landry et al. (1996). The research collaboration networks have a role in achieving different types of outcomes, but there may also be other dimensions of university-industry interaction where these networks may have a role. In the literature on university-industry interaction, the different modes in which the university researchers and companies interact have been discussed extensively (D'Este and Patel, 2007; D'Este and Perkmann, 2007 and 2009; Palmberg, 2008; Nikulainen and Palmberg, 2010). In future research, it would be worthwhile to examine these different modes of interaction, ranging from seminars to R&D contracting, and their intensities while taking into account the role of research collaboration networks and boundary spanning. This would expand our understanding of the role of these networks in various contexts and thus provide more light on the discussion of the importance of interdisciplinary research in modern university-industry interaction.

For policymakers, the findings of this paper highlight the need to take into account the role of interdisciplinary research in academia when promoting university-industry interaction. As the connection between interdisciplinary research and the outcomes is fairly small compared to other factors, these 'control' factors such as challenges associated with interaction with industry as well as the motivation for research should also not be neglected. In particular, policymakers could promote researchers' collaboration with industry through temporary workplace exchanges or visits that are sufficiently long for the researchers to understand industry's needs and thus identify new research ideas and commercial opportunities, which eventually may lead to more tangible outcomes such as patenting and industry funding. Also, challenges related to the ownership of the research results seems to have a negative connection with the outcomes; promoting the university-industry interaction would thus require clear intellectual property rights guidelines so that both academic researchers and companies are motivated to participate in collaboration. Finally, the connection between outcomes and the availability of new research instrumentation suggests that access to state-of-the-art equipment and instruments has a positive relationship with the identification of new research ideas and commercial opportunities. For policymakers, this means that in order to promote academic industry interaction and generate high-quality research, universities should have enough resources to gain access to high-end research instrumentation.

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APPENDIX I – Correlation matrix

		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
Identification of ideas	(1)	1.00																										
Ident. of com. opportunities	(2)	0.67	1.00																									
Funding	(3)	0.70	0.61	1.00																								
Patenting	(4)	0.44	0.61	0.49	1.00																							
Age	(5)	0.06	0.07	0.13	0.19	1.00																						
Publications	(6)	0.05	0.08	0.10	0.21	0.72	1.00																					
Nano-intensity	(7)	0.11	0.08	0.11	0.10	-0.17	0.01	1.00																				
Physics	(8)	-0.10	-0.14	-0.16	-0.22	-0.20	-0.03	0.28	1.00																			
Chemistry	(9)	0.22	0.18	0.24	0.27	-0.03	-0.05	0.30	-0.30	1.00																		
Bio/Medical	(10)	-0.21	-0.07	-0.22	-0.04	0.23	0.20	-0.46	-0.45	-0.33	1.00																	
Multiple degrees	(11)	0.04	0.04	0.02	0.03	0.01	0.05	0.08	0.08	0.17	0.07	1.00																
Industry experience	(12)	0.23	0.23	0.24	0.21	0.21	0.03	-0.03	-0.04	0.01	0.02	0.05	1.00															
Passive researchers	(13)	-0.17	-0.14	-0.19	-0.12	-0.01	0.00	-0.10	0.02	-0.13	0.14	-0.08	0.01	1.00														
Basic research orientation	(14)	-0.27	-0.30	-0.31	-0.27	-0.08	0.00	0.11	0.17	-0.06	-0.05	0.02	-0.19	0.25	1.00													
Identifying com. applications	(15)	0.06	0.05	-0.02	0.07	-0.04	-0.05	0.09	-0.02	0.00	0.06	-0.11	0.00	0.28	0.25	1.00												
Communication problems	(16)	0.03	0.09	0.01	0.07	0.01	0.08	0.02	-0.06	-0.04	0.01	-0.11	0.05	0.26	0.19	0.30	1.00											
Ownership issues	(17)	0.25	0.27	0.27	0.23	0.03	0.06	0.04	-0.12	0.03	0.03	-0.04	0.18	0.04	-0.01	0.15	0.28	1.00										
Lack of business skills	(18)	0.04	0.04	-0.02	0.04	-0.02	-0.04	0.05	-0.11	0.05	0.10	-0.06	-0.03	0.19	0.21	0.51	0.32	0.27	1.00									
Lack of production technologies	(19)	0.15	0.13	0.06	0.08	-0.07	-0.09	0.09	-0.06	0.02	0.03	0.08	0.13	0.19	0.12	0.41	0.32	0.27	0.46	1.00								
Own interest	(20)	0.04	0.03	0.06	0.00	0.17	0.29	0.11	0.01	-0.05	0.06	0.03	-0.12	-0.07	0.06	0.01	-0.02	0.01	0.03	-0.05	1.00							
Supervisor interest	(21)	-0.02	-0.05	-0.04	-0.14	-0.47	-0.44	0.17	0.11	0.10	-0.20	-0.03	-0.08	-0.02	0.06	0.01	-0.08	-0.04	0.03	0.04	-0.09	1.00						
Public funding	(22)	0.10	0.13	0.11	0.11	-0.04	-0.08	0.20	-0.09	0.10	0.00	0.02	0.01	-0.09	-0.05	0.11	0.01	0.07	0.07	0.11	0.13	0.23	1.00					
New instrumentation	(23)	0.25	0.20	0.19	0.11	0.04	0.04	0.33	-0.06	0.26	-0.12	0.02	0.00	-0.07	0.01	0.16	-0.05	0.10	0.17	0.11	0.12	0.17	0.32	1.00				
Visit abroad	(24)	0.06	0.05	-0.01	0.04	0.10	0.20	0.12	0.00	0.00	0.07	0.10	-0.04	0.02	0.20	0.15	0.00	0.00	0.11	0.08	0.22	0.03	0.14	0.20	1.00			
Commercial potential	(25)	0.42	0.50	0.39	0.35	-0.01	-0.05	0.28	-0.07	0.17	-0.12	0.10	0.27	-0.12	-0.31	0.10	0.06	0.24	0.10	0.20	0.09	0.08	0.27	0.24	0.08	1.00		
Publication betweenness	(26)	-0.03	0.00	-0.01	0.00	0.02	0.08	0.02	0.09	-0.05	-0.01	-0.01	0.00	0.06	0.04	-0.03	0.10	-0.01	-0.03	0.01	-0.01	0.06	-0.08	0.03	-0.05	-0.09	1.00	
Patent betweenness	(27)	0.06	-0.03	0.12	0.04	0.06	0.07	-0.04	-0.04	0.11	-0.04	0.17	-0.01	-0.04	-0.04	-0.02	0.07	0.01	-0.02	0.00	0.03	-0.07	-0.04	0.01	-0.02	-0.04	-0.01	1.00