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Influence of partner diversity on collaborative public R&D project outcomes: A study of application and commercialization of nanotechnologies in the Netherlands

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ABSTRACT

Several studies have indicated the importance of public R&D in the transfer and commercialization of nanotechnology. So far, few have focused on university–industry interaction and collaboration performance. In this study, we investigate the impact of technological diversity and value chain complementarity of partners on public nanotechnology R&D projects' performance. We enriched a database on the commercial outcomes of technology research projects from the Dutch Technology Foundation STW. To test our hypotheses, we selected 169 nanotechnology research projects from the database, which started in a five-year period from 1998 until 2003. Project performance was measured five years after completion of the project. Technological diversity has a U-shaped effect on the projects' commercial performance. Findings show a strong positive impact of value chain complementarity of partners on both application development and commercial performance of the projects.. The framework introduced in this study allows an evaluation of the effects of technological diversity and value chain complementarity on application development and the commercial performance of public R&D projects.

1. Introduction

The application and commercialization of nanotechnologies are expected to cut across established knowledge, technological and organizational boundaries and might disrupt traditional industries (Shea, 2005; Walsh, 2004). This suggests that the ability to integrate knowledge (scientific, technological, commercial, regulatory) distributed across professional groups, companies and research organizations is crucial for nanotechnology development (Bozeman et al., 2007; Nikulainen and Palmberg, 2010; Palmberg, 2008; Pandza et al., 2011). Successful technological development in this case requires close collaboration between different actors (Nikulainen, 2010). In this paper we focus on the question: *What is the impact of the diversity of partners in collaborative public nanotechnology R&D projects on the development of innovation performance?*

Recently, Technology and Innovation Management research started to investigate the developments in the field of nanotechnology. A great deal of this research focuses on technological forecasting using different foresight techniques (Salerno et al., 2008), such as patent analysis (Alencar et al., 2007), technology mining (Islam and Miyazaki, 2010), bibliometrics; (Kostoff et al., 2007; Motoyama and Eisler, 2011), scenario analysis (Schmidt, 2008) and analysis of socio-technical co-evolution (Robinson, 2009). These studies tried to identify and define nanotechnology. There is an underlying commonality in these works: nanotechnology is a general purpose technology, and policy implications suggest that, although its economic potential is high, its introduction might lead to a temporary economic downturn, and steps will have to be taken to smoothen the transition to new nanotechnologies.

While this forecasting research investigates technology dynamics at a macro level, we aim to investigate the commercialization of nanotechnology, for which we need a micro level insight into the actual transfer of technology from the public research sector to the private one. Nikulainen and Palmberg (2010) investigated the relationships between the motives of researchers, university–industry interactions, and nanotechnology transfer challenges and outcomes when commercializing scientific knowledge. Their findings show that the most important modes of industry–university interactions in the field of nanotechnology take place in public R&D programs and at conferences

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Our study contributes to the literature on outcomes and commercialization of nanotechnology transfer by focusing on university–industry linkages and the diversity of partners in public R&D projects. In doing so, we describe patterns of collaboration to find commercialization mechanisms for nanotechnology based products. The literature on university–industry collaboration is used as theoretical background to derive the main hypotheses of our study. Hypotheses are tested on a dataset (2000–2008) of 169 public nanotechnology R&D projects, which are aimed at the commercialization of nanotechnology. In each project on average of 5 organizations participated..

We organized the paper as follows. In Section 2, we discuss the literature on technology transfer and industry–university cooperation and develop our hypotheses. In Section 3, we describe the research setting and methods. In Section 4, we present the results. We conclude the paper (Section 5) with a discussion of the research findings and suggestions for further study supporting the management of these complex cooperation processes.

2. Theory and hypotheses

2.1. University–industry collaboration

Universities are increasingly asked to exploit their research not only scientifically but also for the good of the economy, their activities switching from knowledge dissemination to 'innovation–promoting hubs' (Hussler et al., 2010: 508). For the same reasons, national and regional science and technology policies try to advance application through technological and industrial hot spots (Kautt et al., 2007). Studies on knowledge and technology transfer emphasize the broad variety of university–industry interactions that contribute to technology diffusion and valorization (D'Este and Patel, 2007; Perkmann and Walsh, 2007). Scholars have identified various university–industry interaction modes (Arza and Lopez, 2011; Boardman and Ponomariov, 2009), such as contract and cooperative research, licensing, use of lab facilities, personnel mobility, information dissemination through publications and new venture creation. Several authors noted the importance of joint research activities as channels for conveying scientific knowledge to industry (Agrawal and Henderson, 2002). Roessner (1993) and Schartinger et al. (2001) showed that cooperative research is the most important for knowledge transfer, while patents and licensing only account for a small portion. This is in line with the findings of Nikulainen and Palmberg (2010) in the field of nanotechnology, indicating that the dominant mode of industry–university interaction is the public collaborative R&D project. However, Nikulainen and Palmberg (2010) could not find a significant effect of university–industry interaction on the involvement of researchers in nanotechnology, they identified the need for further research into the commercialization of nanotechnology. Pandza et al. (2011) found that nanotechnology research networks are characterized by a high degree of collaborative diversity and raised the issue of how to manage this diversity and the need for further research into the performance of divers collaborative networks. Taken together these studies suggest that for the commercialization of nanotechnology there is a need to better understand university–industry collaborative performance.

Most studies on university–industry collaboration focus on the determinants for the choice of partners in research collaborations, and investigate what partner characteristics affect the formation of a collaboration (Veugelers and Cassiman (2005); Fontana et al. (2006); Arranz et al. (2008); Vonortas and Okamura, 2009). Compared to collaboration formation, the impact of university–industry relations on collaborative performance is much less investigated. In a recent study Petruzzelli (2011) found an inverted U-shaped effect of technological relatedness and a positive effect of prior ties and geographical distance on the innovation performance of university-industry collaborations.

In the body of research on R&D collaboration from a private sector point of view, several studies investigated the impact of collaborative relations on firm performance. (e.g. Miotti and Sachwald, 2003; Faems et al., 2005; Belderbos et al., 2006; Nieto and Santamaria, 2007; Zeng et al., 2010). These studies find support for the positive impact of inter-organizational collaboration on innovation performance and for differences in impact on innovation performance depending on the types of partners that deal with different steps of the value chain. In addition Nieto and Santamaria (2007) found that the partner diversity had the largest effect on the degree of innovation novelty, compared to the separate effects of particular types of partners.

The aim of this paper is to develop an understanding of the role of partner diversity in the performance of multidisciplinary nanotechnology R&D projects. To do so, we firstly follow the argumentation and findings of Petruzzelli (2011), because it is as far as we know one of the few quantitative studies investigating performance of university–industry collaboration. Assuming that the performance effect of technological diversity is similar for all university–industry relations and thus also for nanotechnology projects, we address the project's differential performance effect when technological knowledge is very similar or very different in university–industry collaboration. While Petruzzelli (2011) investigated technological diversity between two partners, we focus on the technological diversity between multiple partners in a R&D project. Furthermore, Petruzzelli (2011) analyzed collaboration success on co-patent relationships and thus investigated the most successful collaborations, while we investigate a much brother spectrum of industry–university relations. In addition, assuming that diversity of partners will have similar effect on project performance, we apply explanations about the effect of partner diversity on firm performance to the situation of collaboration project performance. In the following paragraphs hypotheses are developed about the impact of the technological diversity and value chain complementarity between partners in nanotechnology R&D projects on innovative performance of these projects.

2.2. Technological diversity between project partners

In the innovation literature resources heterogeneity is seen as a crucial condition for technological development (Nelson and Winter, 1982) and inter-organizational cooperation is seen as a means for organizations to combine heterogeneous resources in new ways (Prahalad and Hamel, 1990; Ahuja, 2000). However access to heterogeneous resources is not always a sufficient condition for innovation, as partners need absorptive capacity (Cohen and Levinthal, 1990) to be able to identify, develop and exploit valuable resources of others. For this reason technological similarity between partners is seen as enhancing synergy in collaborative innovation, the higher the technological similarity between partners, the easier it is to align and commercialize the combined technological resources (Cohen and Levinthal, 1990; Hussinger, 2010; Mowery et al., 1998; Lane and Lubatkin, 1998). On the other hand when technological similarity is too high it can have a negative effect on collaborative innovation (Nooteboom, 2000). Therefore, emerging evidence points out an inverted U-shaped effect of technological diversity between partners and innovation performance (Wuyts et al., 2005; Nooteboom et al., 2007; Petruzzelli, 2011). We continue on this path and investigate the performance impact of technological diversity in nanotechnology research projects. In line with the findings of (Petruzzelli, 2011), we formulate the following hypothesis:

Hypothesis 1. Technological diversity between partners in nanotechnology research projects has an inverted U-shaped impact on both application development and commercial performance of these projects.

2.3. Value chain complementarity

Previous research found that different types of R&D collaboration serve complementary purposes. Miotti and Sachwald, 2003 found that technological development of firms is positively influenced by collaboration with research institutes and commercialization of new technology is positively influenced by vertical cooperation. Nieto and Santamaria (2007) investigated the composition of collaborative networks and found that collaboration with suppliers, customers and research organizations has a positive impact on innovation novelty, while cooperation with competitors has a negative impact, and the greatest positive impact on innovation came from having multiple types of partners. Zeng et al., 2010 found that for Chinese SMEs, partnerships with customers, suppliers and other firms play a more distinct role in innovation performance than partnerships with universities, research institutes and government agencies. Moreover, Belderbos et al. (2006) tested whether different types of R&D cooperation are complementary in improving a firm's productivity, they found that customer cooperation enhances the impact of competitor and university cooperation. We assume similar effect of complementarity of collaborative partners on university–industry project performance. Taken together, this leads to the following hypothesis regarding the complementarity contribution of different types of R&D collaboration that deal with different steps of the value chain .

Hypothesis 2. Value chain complementarity between partners in nanotechnology research projects has a positive effect on the application development and commercialization performance of the projects.

3. Methods

3.1. Setting and data

We tested the hypotheses using data on the commercialization activities in collaborative technology research projects funded by the Dutch Technology Foundation STW. STW gives grants to utilization-oriented technology research at Dutch universities and selected scientific research institutes. Through the Dutch Organization for Scientific Research (NWO), STW receives its funding from the Dutch Ministry of Economic Affairs and the Dutch Ministry of Education, Culture and Science. The project partners are the researchers and potential users of the results. The partners provide input as well as financial or other contributions to the project. All potential users of knowledge – knowledge institutions, large, medium-sized and small businesses and those involved in R&D – are eligible for collaboration in the projects. The partners are given the opportunity to work alongside the researchers and be the first to learn of the results. In the period 1992–2009 417 public R&D projects aiming at commercialization are funded by STW with this particular grant.

Firstly, an expert in the field of nanotechnology identified 174 projects as nanotechnology projects applying the National Nanotechnology Initiative's definition: 'Nanotechnology is the understanding and control of matter at dimensions of roughly 1 to 100 nm, where unique phenomena enable novel application' (see Balogh, 2010; Bozeman et al., 2007). The selected 174 nanotechnology projects started in the period from 1998 until 2003. We excluded 5 projects because they had no partners and therefore no outcome and partner characteristics existed so we executed our study on the remaining 169 collaborative projects. These projects represent the majority of the public collaborative public private R&D projects in The Netherlands. The partners most probably almost all organizations, institutes and firms, active in relation to nanotechnology and are as such fit for testing our hypotheses.

Secondly, we listed all the participating organizations (411) in the projects and classified them into six types: firms, governmental agencies, research institutes, hospitals, universities and special interest groups.

Thirdly, we checked the names of participating organizations for duplicates and misspellings, and consolidated firm names up to the holding level. We collected patent information for all partners in the 169 research projects using data from the European Patent Office (EPO). For each participant, patent applications from 1995 to 2002 were collected at the consolidated firm level. In this way, information on 99,730 patents was gathered.

3.2. Variables

3.2.1. Dependent variables

We measured performance five years after the completion of the projects, because performances are likely to lag behind R&D activity. We define *Application development* as the degree to which the project leads to a tangible product such as software, patent, prototype or process description. We used the product generation scale from the STW database, which comes closest to our definition of application development and distinguishes: (1) project prematurely terminated; (2) no tangible product; (3) a temporary design or principle was developed, verification still needed; (4) a product was developed, such as software, a prototype, a process description or a patent. We combined 1 and 2 together into one level because in neither involves a product. *Commercial performance* is defined as the degree to which the project generated revenues. We used the revenue generation scale from the STW database, ranging from: (1) project failed; (2) no revenues; (3) occasionally, bits of knowledge are sold but no revenues from exploitation; (4) continuous stream of revenues from knowledge exploitation. Again, we merged 1 and 2 because at both levels, no revenues were generated. We also combined levels 3 and 4 because of the small number of observations at level 4.

3.2.2. Independent variables

Value chain complementarity is defined as the diversity of value chain roles per project. Assuming that organizations active in the same line of transformational activities have similar roles, we construct a measure of the value chain complementarity of a project that captures the diversity of the project's partner types. The partner types that were identified in the sample were: (1) companies, (2) governmental parties, (3) research institutes, (4) (academic) hospitals/medical institutions, (5) universities/ schools and (6) special interest groups.The measure is based on the Hirschman–Herfindahl index used by Baum et al. (2000) and computes diversity as one minus the sum of the squared proportions of the research project partners with each of the six partner types divided by the project's total number of partners.

Technological diversity is defined as the degree to which there is complete coverage of the eight main patent classes. We calculated the diversity in a project based on the four digit EPO patent numbers. The eight main classes are: (A) Human necessities, (B) Performing operations/ Transporting; (C) Chemistry; Metallurgy; (D) Textiles/Paper; (E) Fixed constructions; (F) Mechanical engineering/Lighting/Heating/Weapons/Blasting; (G) Physics; (H) Electricity. Among the 411 partners, the highest numbers of patents are in Human necessities, followed by Chemistry/

Metallurgy, Electricity, and Physics. Correlation analysis of the eight classes showed a strong correlation between Human necessities and Chemistry/Metallurgy and between Physics and Electricity, implying that in nanotechnology R&D, these fields are combined. Of the 411 unique partners, 182 had one or more patent applications. Of the 169 research projects 12.4% had partners without patents, 32.5% had one partner value chainwith patents.

3.2.3. *Control variables*

We included controls for commitment of partners, network centrality of partners and number of partners. Several studies found a positive effect of commitment in industry–university cooperation success (Davenport et al., 1999; Mora-Valentin et al., 2004; Barbolla and Corredera, 2009). *Commitment of partners in the project* is defined as the degree to which partners actively contribute to the project. We applied the scale from the STW database, which ranges from: (1) commitment failed, no relevant results for partners; (2) partners participated in user committee; (3) partners participated actively and provided some tangible support such as money or materials; (4) partners participated substantially by providing extensive support and/or by arranging cooperation contracts. An additional characteristic that may have an effect on the performance of especially a nanotechnology research project is the involvement of partners who are key players in the innovation network (Meyer and Persson, 1998; Robinson et al., 2007). We controlled for variation in key player participation by including a measure for the centrality of partners, which is computed from the sum of centrality measures of each project participant, divided by the total number of partners. *Network centrality of the partners* is measured by the degree of centrality in the larger network, which counts the number of links a participant has in the nanotechnology research network.

Performance may also vary with the *number of partners*. Therefore, we controlled for the number of partners.

3.2.4. *Analysis*

In the testing of the hypotheses concerning application development, which is a three level ordinal variable, an ordered logistic regression was appropriate. To test the hypotheses concerning the commercial performance of nanotechnology R&D projects a binary logistic regression was applied Tables 1–3

4. Results

Three aspects of the descriptive of our results are worthwhile mentioning (Table 1). Firstly, the value chain complementarity is extremely low with a mean of 0.08 and a maximum of 0.25 given the theoretical range from zero to one. This means that at most three different positions in the value chain were present in any project. Secondly, the application development and the commercial performance are medium interrelated, which means that success of a project is quite mixed and not unequivocal a success or a failure. Thirdly, the number of partners correlates medium with the technological diversity, and its square, which is to a certain extent logical as with growing numbers in the collaboration on the chances on higher technological diversity are higher.

Hypothesis 1 predicted an inverted U-shaped effect of technological diversity on application development and commercial performance. In both occasions the contrary is found (models 4 and 8 in Tables 2 and 3). It could be that this result, especially for the application development, stems from the relation with

Table 1
Range, means, standard deviation and correlations of the variables ($N=169$).

	Range	Mean	S.D.	1	2	3	4	5	6	7	8
Application development	1–3	2.03	0.77	1							
Commercial performance	0–1	1.27	0.45	0.463	1						
Technological diversity	0–8	4.82	2.59	0.030	−0.121	1					
Technological diversity squared	0–64	29.89	21.88	0.019	−0.091	0.960	1				
Value chain complementarity partners	0–.25	0.08	0.06	0.071	0.093	0.117	0.062	1			
Commitment of the partners	1–3	2.02	0.66	0.338	0.360	−0.139	−0.120	−0.110	1		
Network centrality partners	0–8.61	1.23	1.07	−0.143	-0.091	−0.025	0.036	0.085	0.020	1	
Number of partners	1–13	4.98	2.36	0.263	0.074	0.468	0.449	−0.186	0.088	−0.134	1
N of cases 169											

Table 2
Determinants of: Application development of nanotechnology R&D projects.

	1		2		3		4	
	B	s.e.	B	s.e.	B	s.e.	B	s.e.
[Application development=1]	1.616	0.602	2.317	0.686	1.614	0.709	2.135	0.752
[Application development=2]	3.678	0.659	4.426	0.750	3.682	0.757	4.260	0.808
Commitment of the partners	1.019***	0.237	1.078***	0.241	0.999***	0.242	1.037***	0.245
Network centrality partners	−0.267**	0.151	−0.303**	0.160	−0.248**	0.153	−0.288**	0.162
Number of partners	0.191***	0.066	0.227***	0.068	0.217***	0.075	.274***	0.079
Technological diversity in the project			0.046	0.211		0.211	−.077	0.221
Technological diversity squared			−0.011	0.025		0.025	0.000	0.025
Value chain complementarity partners					5.822	2.513	6.394***	2.615
Nagelkerke R^2	0.205		0.209		0.234		0.241	
Chi-square	33.88#		0.66$		5.35$		6.68$	

$N=169$; tested one-sided ; Link function: Logit; #: −2loglikelihood of model −2loglikelihood intercept only; $: −2loglikelihood of this column −2loglikelihood of column 1.

** $p<0.05$.
*** $p<0.01$.

Table 3
Determinants of commercial performance of nanotechnology R&D projects.

	5		6		7		8	
	B	s.e.	B	s.e.	B	s.e.	B	s.e.
Constant	−3.911***	0.857	−3.162***	0.950	−4.915***	1.028	−4.115***	1.089
Commitment of the partners	1.416***	0.321	1.329**	0.324	1.535***	0.337	1.428***	0.339
Network centrality partners	−0.263*	0.204	−0.295*	0.211	−.324*	0.215	−0.370*	0.228
Number of partners	0.038	0.077	0.103	0.090	.084	0.082	0.196**	0.100
Technological diversity in the project			−0.389*	0.264			−0.608**	0.290
Technological diversity squared			0.033	0.032			0.053*	0.033
Value chain complementarity partners					7.115**	3.291	9.756**	3.657
Nagelkerke R^2	0.204		0.228		0.240		0.285	
Hosmer and Lemeshow test (df=8)	4.490		6.870		4.183		8.692	
−2loglikelihood	172.22		168.90		167.29		160.89***	

$N=169$; tested one-sided ; Link function: Logit; Hosmer and Lemeshow is not significant ($p>0.05$).

* $p<0.10$.
** $p<0.05$.
*** $p<0.01$.

the number of partners in the project, the analysis of the effect of technological diversity (and its square) as sole predictors does not suggest this interpretation. These hypotheses are therefore to be rejected.

The value chain complementarity (Hypothesis 2) has the predicted effect and adds about 4% to the explained variance (models 3 and 7 in Tables 2 and 3) in both occasions and somewhat more in model 4 and 8. Hypothesis 2 is therefore not rejected.

5. Conclusions, discussion and further research

With the exception of Mora-Valentin et al., (2004) and Petruzzelli (2011) there is little prior research on the performance effects of university–industry collaboration. For nanotechnology in particular there is a need to gain a better understanding on the performance of divers collaborative networks (Nikulainen and Palmberg, 2010; Pandza et al., 2011). We contribute to the existing research by analyzed the technological diversity and value chain complementarity in multiple partner public nanotechnology research projects and how these affect the project's application development and commercial performance. Our study shows a non significant effect of technological diversity on application development, however it has the same contribution to the explained variance as the results of Petruzzelli (2011). Moreover, results show that value chain complementarity has a positive effect on both application development and commercial performance of the collaboration projects. This is in line with previous research (Belderbos et al., 2006; Nieto and Santamaria, 2007) that found that collaboration with different value chain partners had a positive effect on firm innovation. We showed that these findings also hold for public nanotechnology R&D projects.

A U-shaped effect of technological diversity on commercial performance of the projects is found. This is contrary to the findings of Petruzzelli (2011) and could be an outcome specific to nanotechnology. In the nanotechnology projects, the effect of technological diversity first shows a decrease followed by an increase of application development and commercial performance. This effect seems to match the standard pattern of a general-purpose technology that begins with a productivity slowdown followed by a period of rapid growth, which can be explained by an extended learning process, an initial lack of complementary inputs and/or a rapid loss of skills (Shea et al., 2011).

In line with the study on success factors of R&D cooperation (Mora-Valentin et al., 2004), our results show that the participants' commitment has an overall positive impact on the outcomes of nanotechnology research projects. Contrary to what some studies suggest (Robinson et al., 2007), we found a negative effect, although insignificant, of key player participation on overall project performance. The key players are the most central firms in the nanotechnology research network, and probably participating in several projects. In this case there were about eight large Dutch firms. This result suggests that the links of key players with others in the network does not provide resource benefits. Combined with the positive effect of participant commitment, this suggests that it is preferable to share resources within a project (Ahuja, 2000). Finally, the number of partners in a project have a positive impact on performance, this is in line with the policy of the utilization grand in which R&D projects with many partners are stimulated.

5.1. Implications for further research

University–industry collaboration. Evaluating the performance of R&D collaboration from the point of view of public R&D projects has received only limited attention. The framework introduced in this study allows an evaluation of the effects of partner technological diversity and value chain complementarity on the application development and commercial performance of public R&D projects. From a private sector perspective, there are several studies investigating resource complementarity in dyadic relations and in multi-partner R&D collaboration. From a public sector perspective, we did not encounter any studies on resource complementarity. Prior research could be extended with further research into partner complementarity in public R&D projects. In particular, the impact of partner complementarity on performance allows for more research. This study focused on nanotechnology research projects and could be extended to other general purpose technologies such as information technology and biotechnology.

Network embeddedness. Our finding that firms which are central in the R&D network have a negative effect on project performance, though not significant, requires further research into the benefits and drawbacks of relational ties. By viewing the R&D project from a network perspective, the network embeddedness of the partners facilitating access to complementary resources can be analyzed further (Gnyawali and Madhavan, 2001; Lin et al., 2009; Robinson et al., 2007; Uzzi, 1996).

Incumbents/start-ups, a growing body of studies has highlighted the central role of science-based start-ups in changing technology fields (Avenel et al., 2007; Bozeman et al., 2007; Hung and Chu, 2006; Hussler et al., 2010). Therefore, we suggest further study of the role science-based start-ups play compared to incumbents in the performance in multi-partner research collaboration.

Technological trajectories in nanotechnology. In the case of nanotechnology, Avenel et al. (2007) distinguished two trajectories that the firms can follow, through hybridizing the existing knowledge or via the exploitation of breakthrough knowledge.

However, the effect of these trajectories on firm performance has not been investigated yet. Research on technological performance after mergers and acquisitions (Makri et al., 2010) distinguishes between the similarity and complementarity of technological resources. Technological integration can take place between dissimilar technological domains, or between complementary technologies within a technological domain. With respect to spending research funds in an emerging technology field such as nanotechnology, our findings support the relevance of doing further research on the technological trajectories followed in nanotechnology R&D projects and their U-shaped impact on project performance, thus feeding insight into the process whereby science is transformed into commercial technologies in university-industry collaboration.

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