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Abstract

This paper examines the diversity of firms' linkages to science and their effects on innovation performance for a sample of Belgian firms (CIS-3). While at the sectoral level, links to science are highly related to the sector's R&D intensity, we show that there exists considerable heterogeneity in the type of links to science at the firm level. Overall, firms with a science linkage –which can be of various sorts– enjoy a superior innovation performance, in particular with respect to innovations new to the market. At the invention level, our findings confirm that patents from firms engaged in science are more frequently cited and have a broader technological and geographical impact. However, we show that it is crucial to distinguish between direct science links at the invention level and indirect science links at the firm level in order to detect the positive effects of having these links to science. Therefore, Science and Technology indicators should control for both invention-level and firm-level science links to really account for the effect of these industry-science links.

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SCIENCE LINKAGES AND INNOVATION PERFORMANCE: AN ANALYSIS ON CIS-3 FIRMS IN BELGIUM*

Introduction

An important and recurrent concern in economics has been to understand to what extent science influences technological progress. The answer to this question has profound implications for public policy, notably on the decision as to whether and how to fund public research and investment in basic research by industry. The works by Jaffe (1989) and Adams (1990) have shown the importance of basic research for economic growth while research by Acs, Audretsch and Feldman (1992) and others, have revealed the significant externalities stemming from local academic research. Numerous studies have thus attempted to quantify these effects. The rates of return to publicly funded research, for example, have been estimated at between 20% and 60% (Salter and Martin, 2001). This literature has shown that knowledge flows from universities and public research centers make a substantial contribution to industrial innovation and, consequently, to public welfare.[1]

More recent research suggests that the links to basic research by industrial firms have dramatically increased in the last decade and that firms today manifest a diversity of links. There is evidence of rising university spin-offs (Jensen and Thursby, 2001; Thursby and Thursby, 2002), university-industry collaboration (Liebeskind et al., 1996; Darby and Zucker; 2001; Zucker et al., 2001, 2002), mobility of university researchers (Kim et al., 2005), science-linkage in private patents (Narin et al., 1997; Hicks et al., 2001), and so forth. Narin et al. (1997), for instance, report a threefold increase in the number of academic citations in industrial patents in the United States through the mid-1990s.[2] These patterns suggest an increased opportunity for innovation offered by scientific institutions.

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[1] The importance of academic research for industrial innovation has also been corroborated in studies based on industrial survey and patent statistics (Mansfield, 1991, 1995; Cohen, Nelson and Walsh, 2002).

[2] Narin, Hamilton, Olivastro (1997), Branstetter (2004), and Van Looy et al. *(*2004), have all confirmed an increasing citation to academic publications in patents.

In spite of these growing connections to science, our understanding of the variety and distribution of these links, of how these knowledge transfers take place through these links and how they affect industrial innovation remains unclear. The main incentive for enterprises to engage in industry-science links is to access scientific know-how and knowledge. By providing a map of the research environment and current understanding of science, science helps firms avoid wasteful experimentation by focusing on the most promising research paths, thereby increasing the productivity of their internal research (Evenson and Kislev, 1976; Gambardella, 1992). Past work has focused on research partnerships as a mechanism for firms to engage in industry-science relations (Cockburn and Henderson, 1998; Zucker et al., 2001; Belderbos et al., 2005) and has shown that university-industry connections contribute to increased firm research productivity but that their contribution depends on firms' research capabilities and ability to absorb scientific knowledge. However, due to the highly specific nature of the know-how involved, only a select set of firms within specific industries tend to show strong interest in the scientific know-how offered by universities or other science institutes. Evidence from the European community innovation surveys (CIS) indicate that 31% of the firms characterized as "novel innovators" indicate science to be an important source of information, compared to a mere 4% of all firms who find these information sources important (EC-DGECFIN, 2000). Therefore, it seems that science is more important as a source of information for innovation in those science-based technology fields where new breakthrough innovations (i.e. radical innovations) can be achieved and transferred to new products and processes.

In this article, we shed some light on the debate on industry-science linkages by looking at the "diversity" of linkages to science employed by Belgian firms and their relationship to innovative performance. For this purpose, we use the data available from the CIS-3 (Community Innovation Survey) conducted in 1998-2000, and combine it with information on the use of science by firms through patent and publication information. The science linkages considered in this analysis are: *i)* cooperation with public research centers and universities; *ii)* use of public information sources to innovate; *iii)* citation of scientific literature in patents and, *iv)* involvement in scientific publication. Hence, as a first contribution of the paper, we provide a broader picture of the distribution of different links to science employed by manufacturing firms.

In order to better understand the reliance on science by industrial firms, a second contribution of this paper consists of evaluating whether science linkages enhance industrial innovation and economic performance. Two levels of analysis are presented. First, we relate linkages to science to the different indicators of innovation *at the firm level* (turnover due to innovation and turnover due to market introduction as reported in the CIS 1998-2000 data). Second, we explore the micro-level connections between science and innovation performance, focusing on the *invention (i.e. patent) level*. For this, we restrict the sample to patenting firms and compare the differences in patent quality (forward citation) between patents by firms with science linkages vis-à-vis patents of other firms. In this way, this work provides an evaluation of the effectiveness of science linkages in enhancing technological performance by looking at the quality of private inventions.

This paper consists of four sections. Section I presents a summary of the literature and reviews previous empirical work on the value of science for industrial innovation. Section II describes our data, the frequency of science link strategies, and the adoption of science linkages across industries. Section III presents an evaluation of the relationship between science linkages and firms' innovation performance. The final section concludes and identifies some policy implications.

1. The value of Science

Using a variety of methodologies, economists have for a long time attempted to assess the economic payoffs of basic research. Relying on the assumption of informational properties of basic research (non-rival and non-excludable; Arrow, 1962; Dasgupta and David, 1994), economists, such as Griliches (1979) and Adams (1990), have shown the important contribution of basic research (e.g. public research expenditures and scientific publications) to economic growth. Complementary research based on survey studies, has provided an alternative estimate of the contribution of basic research to industrial innovation and economic performance. In a survey of 76 U.S. firms in seven industries, Mansfield (1991) obtained estimates from company R&D managers on what proportion of the firms' products and processes over a 10-year period could not have been developed without academic research. He found that 11% of new product innovations and 9% of process innovations would not have been developed (without substantial delay) in the absence of recent academic research; these innovations represented respectively 3% and 1% of sales.

Both the 1983 Yale Survey and the 1994 Carnegie Mellon Survey of R&D have also shown the relevance of university research for industrial innovation (Cohen et al., 2002). According to the 1994 Carnegie Mellon Survey, American firms considered publishing by universities and patenting among the most important sources of knowledge to innovate.[3] Similar findings have been reported for European firms. In a survey of Europe's largest industrial firms, Arundel and Geuna (2004) find that public science is among the most important sources of technical knowledge for innovative activities.

Several advantages have been associated with the use of science to account for the innovation performance of firms. These include an increase in productivity and the level of applied research effort (Evenson and Kislev, 1976), substantial gains in overall R&D productivity (Henderson and Cockburn, 1996; Gambardella, 1992), the development of absorptive capacity (Arora and Gambardella, 1990; Cockburn and Henderson, 1998), and labor cost reductions (Stern, 1999), among others. Science reduces the incidence of duplication of effort (Arrow, 1962; Nelson, 1982; Dasgupta and David, 1994). As science provides us a map of the technological landscape, it allows private research to focus on the most promising technological venues, avoiding thereby wasteful experimentation (Fleming and Sorenson, 2004).[4] Furthermore, the development of a higher absorption capacity related to the generality of basic research has frequently been argued to be one of the main advantages of conducting science. It permits the firm to more easily identify and integrate external information, enhancing the productivity of internal research (Cohen and Levinthal, 1989, 1990).

Other benefits are associated with the recruitment of scientists where the adoption of pro-publication incentives for employees helps firms attract high quality academic researchers whose economic value might frequently be higher than their actual remuneration. Stern (1999)

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[3] The results indicate that the key channels through which university research impacts on industrial R&D include published papers and reports, public conferences and meetings, informal information exchange, and consulting.

[4] According to Fleming and Sorenson (2004), scientific knowledge differs from that derived through 'local' search within the firm -which is closely related to firms' prior research activities-, in that scientific endeavor attempts to generate and test theories and fundamental ideas, while local search is focused on finding new technological solutions within a predetermined pool of knowledge.

has shown that researchers looking for academic reputation, may want to pursue research projects leading to publications and are, therefore, prompt to accept lower salaries in exchange for permission to keep up with scientific research. These researchers provide value along two dimensions; they not only generate important labor costs reductions but also constitute a "bridge" ('*gatekeepers*' and '*boundary spanners*') with the scientific or academic world.

In spite of such apparent benefits, the adoption of science by private firms remains limited to a very specific kind of organization. Due to the highly specific nature of the know-how involved, only a select set of firms within specific industries tend to show strong interest in the scientific know-how offered by universities or other science institutes. A number of conditions required in order to successfully embrace science have been put forward. Engagement in science is not costless; it is highly conditional on human capital and the adoption of new organizational practices (Gambardella, 1994; Cockburn et al., 1999). The need for new information on innovation differs across industries and is highly dependent on the degree of maturity and the emergence of new technologies (Nelson and Winter, 1982). When industries are shaken up by technological change for which their competences have become obsolete, they are required to cross organizational and industry boundaries and engage in networking with the new actors.

Nevertheless, for firms seeking to overcome their lack of upfront knowledge through cooperation with universities and public research centers, the interaction is not an easy task. The literature has shown that industry-university links are subject to important tensions regarding intellectual property, access and dissemination policies (open science is by definition based on early and large-scale diffusion through publication), and others, inhibiting the chances of successfully translating scientific information into new products (Jensen and Thursby, 2001; Thursby and Thursby, 2002; Hall et al., 2001; Poyago-Theotoky et al., 2002). For instance, in a survey-based study of 38 Advanced Technology Projects (ATP), Hall et al. (2001) found that projects with university involvement tend to be in areas involving "new" science and therefore experience more difficulty and delay but also are more likely not to be aborted prematurely.[5]

Predominantly focused on the firm-level of analysis, the empirical literature has previously assessed the role of scientific connections, notably partnerships with university researchers, on firm performance (e.g. Audretsch and Stephan, 1996; Zucker et al., 1998; Cockburn and Henderson, 1998). Using university collaboration as a science link, these papers seem to support the hypothesis that these links boost internal R&D investment (Adams et al., 2000), innovation productivity and sales (Belderbos et al., 2005).[6] While they provide little explanation about the process through which science affects private innovation, the studies relying on the "production function" have found that science involvement and ties with academic star scientists lead to more technology (Henderson and Cockburn, 1996; Zucker et al., 2002; Cockburn and Henderson, 1998); more "important" patents: i.e. international patents (Henderson and

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[5] In a sample of 62 U.S. university licensing officers, Jensen and Thursby (2001) find that over 75% of the inventions licensed by these universities were in a very early or embryonic stage. Furthermore, 71% of the inventions licensed required cooperation between the professor and the licensing firm in order to commercialize a product successfully. Using the CIS for Belgium, Veugelers and Cassiman (2005) find that cooperation with universities is formed whenever risk is not an important obstacle to innovation.

[6] For instance, Lööf and Broström (2004) have found complementarities between internal R&D and collaboration with universities: the average R&D firm that cooperates in innovation with universities spends more money on R&D and is more likely to apply for patents compared with an almost identical R&D firm which has no such collaboration.

Cockburn, 1994), and a higher average of quality-adjusted patenting (Zucker and Darby, 2001; Zucker et al., 2002).

The work of Cockburn and Henderson (1998) has shown that not only absorption capacity (Cohen and Levinthal, 1989; Kamien and Zang, 2000) in basic research but also closeness to scientific communities are important factors. Using data on co-authorship of scientific papers for a sample of pharmaceutical firms, they show that firms connected to science show a higher performance in drug discovery and that this connectedness is closely related to the number of star scientists employed by the firm.[7] Zucker et al. (1998) and Darby and Zucker (2001, 2002) found that recruitment of star scientists predicts firm entry into biotechnology (by new and existing firms) both in the United States and Japan, while Darby and Zucker (2005) recently provided evidence that firms enter nanotechnology where and when scientists are publishing breakthrough academic articles.[8] For biotechnology in Japan, Darby and Zucker (2001) show that collaborations between particular university star scientists and firms have a large positive impact on firm research productivity, increasing the average firm's biotech patents by 34 percent, products in development by 27 percent, and products on the market by 8 percent as of 1989-1990. Zucker et al. (2002) found that the impact of 'tied' star scientists (those that collaborate with firms) on patents and the number of products in development were significantly greater, exceeding the effects of all other scientists from top research universities working with the firm; no effect was reported for untied science.

II. The diversity of Linkages to Science

Data on firms' research strategies comes from the Third Community Innovation Survey (1998-2000) conducted by Eurostat in Belgium in 2000. Two methods were employed in the CIS-3 for Flemish firms. First, from a population of 9292 firms (those having more than 250 employees), 2726 firms were contacted by traditional mail. From this sample, 684 firms replied and answered correctly the survey, giving a response rate of 25.1%. Given such a low score, a second round of questionnaires was sent out electronically using the CAPI (Computer-Aided Personal Interview). A total of 1471 responses was obtained using the two methods. In this paper, we limit our sample to the 842 manufacturing firms that are engaged in innovation activities and we define the following linkages to science:

i) A dummy indicating whether the firm has been engaged in formal cooperation in R&D (status) with universities or government research centers (both national and international).

ii) A dummy indicating whether the firm considers public information to be a very important source for innovation (firms scoring "3" on a scale of three where the use of scientific information is considered very important).

[7] Differences in the effectiveness with which a firm accesses the upstream pool of knowledge correspond to differences of up to 30% in the research productivity of firms.

[8] Furthermore, they report a similar pattern to that reported previously in biotech: breakthroughs in nanoscale science and engineering appear frequently to be transferred to industrial application with the active participation of discovering academic scientists.

iii) A dummy indicating whether the firm is engaged in collaboration with universities or public research centers and, at the same time, considers public information to be a very important source of innovation.

iv) A dummy indicating whether the firm has been engaged in publication activity, giving a value of 1 if the firm has published at least one article. Data on publications is collected from the ISI-Web of Knowledge database. A publication is considered scientific if it is found in the ISI Web of Knowledge (with publication dates 1990-1995).

v) A dummy variable indicating whether the firm has patents (or at least one patent) that contains references to scientific papers (at least one scientific non-patent reference), which is or are found on the ISI-Web of Science. We have looked for the patents for our CIS-3 firms in the European patent database (EPO ESPACE-B database). 1186 granted patents at the European Patent Office with grant dates between 1995-2001 were found, for a total of 79 firms reported in the CIS-3.

Tables 1 and 2 show the distribution of firms across the different science linkages and across sectors. Corroborating previous research, the use of science and cooperation with universities and public research centers by Belgian firms is limited to a few firms but there is some diversity in the ways scientific knowledge is accessed. The first finding that emerges from these tables is the low frequency of science connections relative to the population (manufacturing firms). 74.82% of these firms do not have any linkage to scientific communities. Not surprisingly, Table 2 shows that the low R&D-intensive industries have the highest percentage of firms not having any connection to science (82%) while the opposite is found in the high R&D-intensive industries. Confirming previous studies, this latter group of industries reports the highest percentage of firms engaged in scientific linkages (relative to the total number of firms): 25% of the firms are engaged in cooperation with public institutions, 33% consider the use of public information to be very important for innovation, while 16% claim to be engaged in both strategies. This is related to the sectoral correlation seen in Table 1 where Electronics; and Medical and precision instruments followed by chemicals (within pharmaceuticals), and petroleum score high on all types of science links. However, some interesting industry variation in the relative use of science links emerges across sectors from Table 1. Firms in Wood, Printing and Publishing or in Glass/Ceramics find public information sources relatively more important than engaging in cooperative agreements. On the contrary, firms in the Medical and precision instruments, Electronics or Vehicles sectors rely more on cooperation than on public information for their connections to science. Firms reporting citation of the scientific literature in their patents are few. They represent less than 3% of the population of manufacturing firms in the CIS, casting some doubt on the relevance of such indicators for understanding links to science in the overall population of firms. If we consider only the population of patenting firms, 24% (19 firms out of 79) of these firms report a science linkage in their patents.

Figure 1 goes a step further in showing the overlap between different science linkage strategies. The diversity at the firm level is striking. While at the sector level there seems to be substantial correlation between strategies, at the firm level we find considerable diversity. The figure suggests that firms citing science are not necessarily only those relying on cooperation or those considering the use of public information to be very important. The overlap between cooperation and use of public information only occurs in 45 firms; of these, only 5 report citations of science in their innovation outputs measured by patents. 7 firms that do not report any science linkage appear as having scientific references in their patents; of these, 5 belong to the medium R&D-intensive industries. Similarly, very few firms (9) are directly involved in open science through publication, and more surprisingly, 5 of these 9 firms are found in the medium-low R&D-intensive industries.[9] These simple descriptive statistics not only corroborate the heterogeneity that exists in the means of accessing scientific knowledge but also reveal that some additional information is found in the science-linkage reported in publications and patents.

III. Performance of Science Linkages

In this section we evaluate whether science linkages enable firms to achieve higher innovation and economic performance. According to the literature previously mentioned, it is expected that firms connected to science will develop comparative advantages in the production of innovation and, notably, in the production of breakthrough innovation. By facilitating the absorption and understanding of fundamental knowledge, science linkages allow firms to exploit new discoveries, upgrade internal technological competences, and detect new opportunities for industrial innovation. We present two levels of analysis. First, we relate linkages of science to the indicators of innovation and economic performance at the firm level reported in the CIS 1998-2000 data. The key measure of innovation is innovation new to the market, and the indicators of economic performance are turnover due to innovation and turnover due to market introduction.

Second, we provide an additional measure of innovation performance within the firm at the invention level, but controlling for firm-level science links. We compare the differences in the quality (forward citation)[10] of patents from firms with science linkages vis-à-vis patents from other firms, for the sub-sample of patenting firms. Previous empirical research has shown that academic patents, because they rely on more fundamental knowledge, are broader in scope and cited more frequently than private patents (e.g. Jaffe et al., 1993; Henderson et al., 1998). Analyses of patent citations find that academic papers and university patents are more frequently cited than their equivalents from private firms, suggesting that public science is an important input for the innovative activities of firms (Jaffe et al., 1993; Narin et al., 1997). However, there is no evidence concerning the effectiveness of science to account for the technological impact of private patents.[11] Thus, by looking at the invention level, we seek to validate the significance of citation to scientific literature in patents and assess whether these

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[9] We follow the criteria used by the OECD (OECD Science and Technology, 2001). Manufacturing industries are classified in three different categories of technological intensity: high technology, medium technology (grouping medium-high technology and medium-low technology), and low technology. High technology industries include (ISIC. 3): Aerospace, Office & computing equipment; Drugs & medicines, Radio, TV & communication equipment. Medium Technology groups the two classes distinguished by OECD: Medium-high technology industries (Scientific instruments, Motor vehicles, Electrical machines excl. commun. equip., Chemicals excl. drugs, Other transport, and Non-electrical machinery) and Medium-low technology industries (Rubber & plastic products, Shipbuilding & repairing, Other manufacturing, Non-ferrous metals, Non-metallic mineral products, Metal products, Petroleum refineries & products, Ferrous metals). Low-technology industries are: Paper, products & printing; Textiles, apparel & leather; Food, beverages & tobacco; and Wood industries.

[10] We follow past research on patent quality (e.g. Henderson et al., 1998; Harhoff et al., 1999) and use the number of forward citations received by a patent as an indication of their technological impact and economic importance.

[11] Researchers have attempted to control for the nature of the organization owning the patent; e.g. public and private organizations, universities versus corporations (Henderson et al., 1998).

(few) firms are indeed capable of a higher technological performance either through a direct reference to science or an indirect link at the firm level.[12]

III.A. Science linkages and Economic Performance

Table 3 provides some descriptive statistics and t-tests for the comparison of means across linkages. It gives the means for R&D intensity, firm size, and the measures of innovation and economic performance broken down by science linkage. The frequencies of firms that declare innovation new to the market are also reported in the last row. Not surprisingly, firms with at least one science link (column 2) have a higher turnover, more employees and a high R&D intensity. At the same time –corroborating the hypothesis advanced in the literature– firms with science links have a higher percentage of sales from new or improved products (innovation turnover ratio) and a higher percentage of sales from innovative products that are new to the market (as opposed to new to the firm). Firms that have science linkages also show a higher frequency of innovations new to the market (0.47% versus 0.38%). When comparing different science linkages, firms declaring a cooperation with public institutions and also declaring the use of public sources of information as very important (column 5) have a high frequency of introduction of innovation new to the market (44%). However, the group of firms which has scientific references in their patents (column 7) has the largest percentage of firms that have introduced radical innovations (63%). Firms with this science link also display the highest innovation turnover ratio and turnover due to market introductions. However, these firms are also larger and have a significantly higher R&D intensity. While firms with different links do display significant differences in size and R&D intensity, the differences in innovation output are not significant.[13]

The correlation matrix in Table 4 offers additional insights on the correlation between science linkages and performance. Consistent with our finding about the diversity in science links of firms, we find that having a link (column 1) has the highest correlation with the innovation turnover ratio, the new market innovations turnover ratio and the new market introduction indicator, while no one specific link seems to account for this positive effect. In addition, perhaps with the exeption of the important role played by public information, all correlations are stronger for new market introductions relative to overall innovation.

III.B. Science linkages and quality of patents

We now look at the differences in the quality of inventions (patents) with respect to the linkages to science. The sample consists of 1161 patents from 79 firms for which patents from the European Patent Office have been found. These are patents with grant dates between 1995-2001. Their forward citation rate is computed up to the most recent year available in our EPO-ESPACE B database, which is 2003. Past research has shown that the number of citations a patent receives is closely associated with its technological importance, and social value (Trajtenberg, 1990) and correlated to the renewal of patents, the estimated economic value of

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[12] Some researchers consider (e.g. Jaffe et al., 1993) patent and non-patent citations as a “noisy signal” of knowledge flows, with examiners adding much of the noise. As patent and non patent references originate from the examiner revision of the prior art in the European Patent Office, citations may rarely reflect or coincide with the science used by inventors.

[13] Small sample size is clearly an issue here.

inventions and patent opposition (Lanjouw and Schankerman, 1999; Harhoff et al., 1999; Hall et al., 2000).

We have also computed two indicators of technological impact based on forward citations: generality and geographical dispersion. The generality measure has been used as an indication of a patent's impact. A high generality score suggests that the patent presumably had a widespread impact, in that it influenced subsequent innovations in a variety of fields (Hall et al., 2001). This indicator is built as a Herfindahl index (Jaffe et al., 1997; Hall et al., 2001): $generality = 1 - \sum_{i}^{ni} s_{ij}^{2}$, where s_{ij} denotes the percentage of citations received by patent i that belong to patent class j, out of n_i patent classes (note that the sum is the Herfindahl concentration index). The index of geographical dispersion is built in a similar way (1-Herfindhal index of geographical concentration).

The breakdown of patent quality measures across the science linkages of firms is reported in Table 5, including some t-tests (one-tailed) on the comparison of means. As expected, firms which have at least one link to scientific communities report a higher frequency of being cited, appear more general in scope (are more cited across different technology classes, IPC) and have a higher geographical dispersion. However, the difference in means is significant (at 10%) only for geographical dispersion and the frequency of being cited at least once (dummy for forward citation). Firms that cooperate or use public sources of information report 0.70 citations on average and firms involved directly in science through publications report an average of 0.72 forward citations. However, these effects are only marginally significant. We confirm the superior performance in terms of patent quality of firms engaged in science linkages: firms engaged in cooperation or considering public information to be very important; and notably, firms engaged in publication have a higher citation likelihood and higher mean of forward citations compared with patents from firms lacking such linkage (the t-tests are however weakly significant).

Upon comparing patents with scientific references (NPRs) and patents without scientific references, we find that patents without NPRs are more likely to be cited (33% versus 24%) and have a higher mean of forward citations, but patents with NPRs are more general and more geographically disperse. The difference in means between patents having scientific NPRs and those lacking such references are significant only for generality and forward citation probability. This suggests that while patents with scientific references protect broad technologies, more applied patents –patents without scientific references– actually capture the value for the firm. Thus, patents citing a scientific publication appear to cover more fundamental knowledge and they are therefore more likely to be cited across a broad range of technology classes and countries. However, this kind of patent is less likely to be cited and shows no differences from the other patents in the average number of citations received. This finding may suggest that it is not easy for everyone to invent around basic patents and that those who cite such patents may be a very specific kind of inventor who is able to advance technology using very upfront knowledge.

Finally, in Table 6 we control for firm-level science links and compare patent quality between firms with and without science links. In the first panel, we consider only firms with scientific publications and look at the quality of patents with and without scientific references. We confirm that patents with scientific references are more general and citations have a higher geographical dispersion, but they are less likely to be cited. However, and more interestingly, comparing the forward citations of patents without scientific references from these firms with patents without scientific references from other firms (that have no publications), we find that these patents are more likely to be cited and receive more citations. Our interpretation is that firms with scientific publications not only have patents with scientific references, but also have a higher quality of applied patents thanks to their more basic knowledge of the technology. This result is confirmed for firms that consider public sources of information to be very important. Patents from firms that engage in cooperation –with and without NPRs– appear to be superior to their counterparts –those from firms not engaged in cooperation– in terms of citation likelihood. We, therefore, conclude that controlling for firm-level science links when evaluating patent quality is crucial for detecting these science links' innovation performance effect: the higher new to market innovation content.

IV. Conclusions

This paper examines the variety of linkages to science and their association with innovation performance for a sample of Belgian firms (CIS-3). We identify different ways of accessing scientific knowledge by means of CIS indicators and add additional measures to the use of science by firms by analyzing publication data and citations to science in these firms' patents. We confirm findings in the literature that firms with science linkages seem to enjoy a superior innovation performance. Furthermore, we show that, at the invention level, patents from firms with links to science are more frequently cited and have a broader technological impact.

While our sample of firms is limited, we nevertheless provide some clear direction for the development of indicators for these Industry – Science Links (ISL):

- There are a diverse set of possible indicators of ISL, such as cooperation with public research institutes and universities; the importance of public information; publications by the firms; references to scientific literature in the firms' patents; etc.
- While at the industry level ISL is correlated with the industry's R&D intensity, there exists a considerable variation at the firm level, i.e. there is not that much overlap between different types of ISL at the firm level.
- No one indicator is sufficient to account for the effect of ISL on innovation performance. Having a link to science is highly correlated with the innovation performance of firms, particularly with relation to, products new to market, but no single indicator seems to determine this effect.
- At the invention level, we distinguish between the effect of direct science links and indirect –firm-level science links on patent quality. Direct science links, the references to science in the patents, are related to more general and more widely cited patents. This link, therefore, captures the depth of the firm's technological knowledge base. The indirect science link at the firm level (publications, cooperation, public information) demonstrates that patents without any direct science link are more widely cited than comparable patents of firms without such an indirect link to science.

In conclusion, our results indicate that several indicators need to be tracked to obtain a representative picture of a country's ISL activity. Furthermore, to bring out these links' true effect, it is necessary to take into account firm- and invention-level indicators.

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Figure 1

Linkages to Science by Flemish Firms (CIS 3)

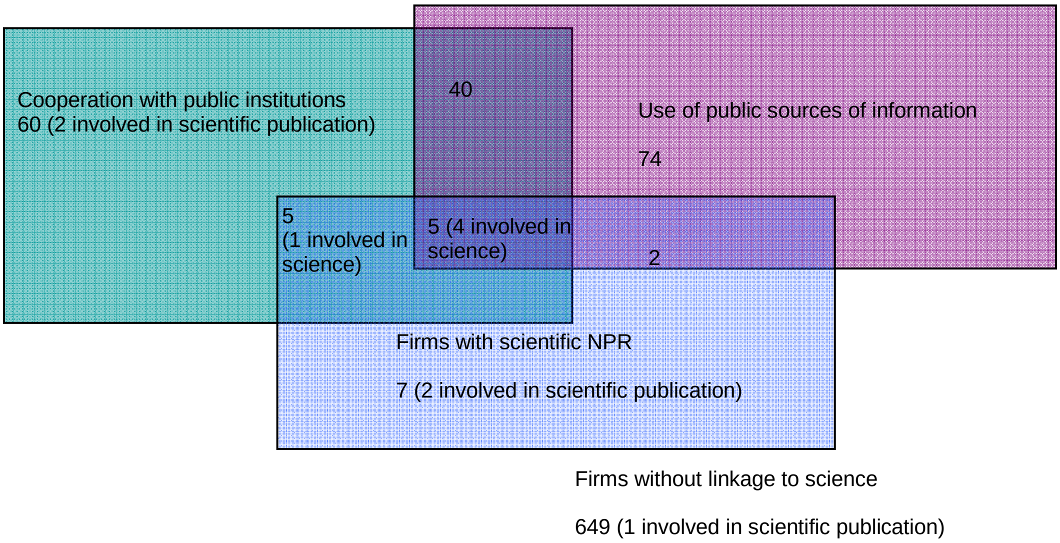

Table 1: Distribution of Firms across Industries and Type of linkage to Science

Industry	Number of firms	Firms without links to science	%	Cooperation with public institutes = 1	%	Use of public information: = 1	%	Cooperation and use of public information	%	Firms with patents	%	Table 1	%	Firms with publications	%
Food and tobbaco	74	59	79,73%	9	12,16%	8	10,81%	2	2,70%	3	4,05%	0	0,00%	0	0,00%
Textiles	68	55	80,88%	9	13,24%	8	11,76%	4	5,88%	2	2,94%	0	0,00%	0	0,00%
Wood, printing, publishing	82	69	84,15%	3	3,66%	9	10,98%	1	1,22%	4	4,88%	1	1,22%	0	0,00%
Chemicals, petroleum	85	54	63,53%	14	16,47%	16	18,82%	7	8,24%	10	11,76%	5	5,88%	3	3,53%
Rubber and plastic	84	63	75,00%	13	15,48%	14	16,67%	7	8,33%	10	11,90%	1	1,19%	1	1,19%
Glass, ceramics	39	31	79,49%	3	7,69%	4	10,26%	1	2,56%	2	5,13%	1	2,56%	1	2,56%
Metals, metallurgy	121	91	75,21%	14	11,57%	19	15,70%	7	5,79%	15	12,40%	3	2,48%	3	2,48%
Machinery, equipment	114	85	74,56%	14	12,28%	16	14,04%	6	5,26%	16	14,04%	4	3,51%	0	0,00%
Electronics	56	33	58,93%	14	25,00%	11	19,64%	4	7,14%	9	16,07%	2	3,57%	0	0,00%
Medical and precision instruments	18	8	44,44%	4	22,22%	8	44,44%	4	22,22%	4	22,22%	2	11,11%	0	0,00%
Vehicles	62	48	77,42%	10	16,13%	5	8,06%	1	1,61%	3	4,84%	0	0,00%	**0**	0,00%
Furniture	39	34	87,18%	3	7,69%	3	7,69%	1	2,56%	1	2,56%	0	0,00%	**0**	0,00%
Total	**842**	**630**	**74,82%**	**110**	**13,06%**	**121**	**14,37%**	**45**	**5,34%**	**79**	**9,38%**	**19**	**2,26%**	**8**	**0,95%**

Note: Only Cooperation with Public Institutes: firms that declare cooperating with universities and/or public research institutes (either national and international) as their only method of accessing scientific knowledge. Only Use of Public sources: firms that consider public information sources as very important for innovation (score=3). The sources of information are: universities or other higher education institutes, government or private non profit research institutes and professional conferences, meeting and journals.

Table 2: Distribution of Firms across groups of Industries and Type of linkage to Science

	Number of firms	Firms without links to science	%	Cooperation with public institutes = 1	%	Use of public information: on = 1	%	Cooperation and use of public information	%	Firms with patents	%	Scientific references in patents = 1	%	Firms with publications	%
Low R&D-ntensive Industries	263	217	82,51%	24	9,13%	28	10,65%	8	3,04%	10	3,80%	1	0,38%	0	0,00%
Medium-Low R&D-Intensive Industries	257	197	76,65%	31	12,06%	38	14,79%	16	6,23%	28	10,89%	5	1,95%	5	1,95%
Medium-High R&D-Intensive Industries	271	194	71,59%	42	15,50%	38	14,02%	13	4,80%	31	11,44%	7	2,58%	2	0,74%
High R&D Intensive-Industries	51	22	43,14%	13	25,49%	17	33,33%	8	15,69%	10	19,61%	6	11,76%	1	1,96%
Total	**842**	**630**	**74,82%**	**110**	**13,06%**	**121**	**14,37%**	**45**	**5,34%**	**79**	**45,74%**	**19**	**2,26%**	**8**	**0,95%**

Note: We follow the criteria used by the OECD (OECD, 2002). High-technology industries include (ISIC. 3): Aerospace, Office & computing equipment; Drugs & medicines, Radio, TV & communication equipment. Medium Technology groups the two classes : Medium-high technology industries (Scientific instruments, Motor vehicles, Electrical machines excl. commun. equip., Chemicals excl. drugs, Other transport, and Non-electrical machinery) and Medium-low technology industries (Rubber & plastic products, Shipbuilding & repairing, Other manufacturing, Non-ferrous metals, Nonmetallic mineral products, Metal products, Petroleum refineries & products, Ferrous metals). Low-technology industries are: Paper, products & printing; Textiles, apparel & leather; food, beverages & tobacco and wood.

Table 3: Linkages to Science and Firm Performance

Variable	No linkage to science	At least one linkage science	Cooperation to with public institutes	Use of public information	Cooperation and use of public information	Scientific references in patents	Firms with publications
	1	2	3	4	5	6	7
R&D Intensity (per employee)	76.49672	210.15***	258.46***	191.804**	290.29**	540.31**	510.0542
Employees	122.0722	440.373***	637,69***	259,84	477,04**	1739,37***	2309.125**
Turnover sales	1117340,00	5649051***	8279243***	3477041*	7210230**	22100000**	3.12e+07**
Turnover due to Innovation	0.1002181	0.2010638***	0,1851818**	0,194***	0,15	0,2452632**	.1125
Turnover due to new market introductions	0.0295483	0.0843085***	0,0959091***	0,0703306**	0,082*	0,1336842*	.04125
New Market Introductions	0.38	0.47	0.42	0,36	0,44	0,63	0,57

Note: The significance of the t-tests (Pr(T<t) in the comparison of means between the group and the other firms lacking such a link are noted by: * at 10%, ** 5%, *** 1%.

Table 4: Correlation matrix

		1	2	3	4	5	6	7	8	9	10	11	12
At leat one link to science	1	1.0000											
Cooperation with public institutions	2	0.7109*	1.0000										
Use of public information	3	0.7512*	0.2933*	1.0000									
Cooperation and use of public info.	4	0.4357*	0.6130*	0.5800*	1.0000								
Scientific references in patents	5	0.2786*	0.1784*	0.0973*	0.1417*	1.0000							
Firms with publications	6	0.1631*	0.1653*	0.0891*	0.1807*	0.5286*	1.0000						
R&D intensity (per employee)	7	0.0696	0.0673	0.0410	0.0572	0.1520*	0.0906	1.0000					
Employees	8	0.2458*	0.3190*	0.0484	0.1250*	0.4391*	0.3638*	0.0977*	1.0000				
New Market Introduction	9	0.2228*	0.1963*	0.1527*	0.1356*	0.1564*	0.0593	0.0714	0.1133*	1.0000			
Turnover sales	10	0.2303*	0.2943*	0.0675	0.1490*	0.3746*	0.3299*	0.1295*	0.7913*	0.1080*	1.0000		
Turnover due to Innovation	11	0.2001*	0.1170*	0.1424*	0.0259	0.0898*	-0.0029	0.0532	0.1553*	0.2769*	0.0603	1.0000	
Turnover due to new markeet introduction	12	0.1808*	0.1712*	0.0957*	0.0793*	0.1138*	-0.0042	0.1100*	0.0584	0.5836*	0.0451	0.5004*	1.0000

Note: * signicant correlation at 5% and better.

Table 5: Patent quality and Science linkages

	All	No link	At least one link	Cooperation with public institutions	Use of public sources	Cooperation and use of public information	Scientific firm (publications)	Patents with NPR	Patents without NPR	7 vs 8
	1	1	2	3	4	5	6	7	8	9
Forward Citation[b]	0,67	0,70	0,67	0.69*	0.71*	0,65	0.72*	0,64	0,67	0,193
generality[b]	0,10	0,09	0,10	0,10	0,10	0,09	0,10	0,17	0,08	-2.14*
geographical impact[b]	0,22	0,14	0.188*	0,19	0,19	0,20	0.194*	0,23	0,18	-1.14
Dummy forward citation[a]	0,33	0,30	0,33*	0.34*	0.34*	0.34*	0.35**	0,24	0,33	4.26*

Note: * significance at 10%, ** at 5%. At least one link: firms that cooperate or use public information or are involved in scientific publications. The forward citations constitute the number of citations received by other EPO patents. The measures of generality and geographical impact as well as the tests for the comparison of means (and proportions) constitute are calculated only on the patents having received forward citations. a: Pearson Chi-square test on the significance of the relationship between the two groups (categorical variables); b: t-test on the significance of the difference in the means.

Table 6: Science citation and science linkages

	Firms with scientific publications		**Firms without scientific publications**	
Patent Indicators	With NPR	Without NPR	With NPR	Without NPR
	1	2	3	4
Forward dummy[a]	0,25	0.36**	0,22	0,27
Forward citation[b]	0,71	0.72*	0,407	0,55
generality[b]	0,16	0,09	0,24	0,084
geographical impact[b]	0,21	0.19*	0,32	0,14
	Firms that cooperate with public institutions		**Firms that do not cooperate with public institutions**	
Patent Indicators	With NPR	Without NPR	With NPR	Without NPR
	1	2	3	4
Forward dummy[a]	0.27*	0.35*	0,058	0,27
Forward citation[b]	0.73	0,69	0,11	0,57
generality[b]	0.16[c]	0,091	0,5	0,072
geographical impact[b]	0,23	0,18	0,22	0,15
	Firms that consider public sources of information to be very important		**Firms that do not consider public sources of information to be very important**	
Patent Indicators	With NPR	Without NPR	With NPR	Without NPR
	1	2	3	4
Forward dummy[a]	0,25	0.355*	0,22	0,29
Forward citation[b]	0,71	0.71*	0,407	0,57
generality[b]	0,16	0,09	0,24	0,08
geographical impact[b]	0,21	0.189*	0,32	0,15

Note: * significance at 10%, ** at 5%.The measures of generality and geographical impact as well as the tests for the comparison of means are calculated only on the patents which have received forward citations. a: Pearson Chi-square test on the significance of the relationship between the two groups (categorical variables); b: t-test on the significance of the difference in the means. c: the t-test has not been calculated since there is only one observation for patents with non-patent references from firms that do not cooperate.