External knowledge sourcing: Science, market and the value of patented inventions*

Cédric Schneider†
K.U. Leuven, Belgium
and
Copenhagen Business School, Denmark

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Abstract

This paper analyzes the choice between alternative sources of knowledge in patented inventions. Inventors can use scientific and/or market-oriented sources of knowledge. We formally test whether these two types of knowledge acquisition are complementary or substitutable in the value of patented inventions. The results suggest that simultaneous exploitation of different knowledge inputs is "subadditive" since inventors would have to manage assimilation and integration of disparate items of external knowledge stemming from distant technology contexts.

Keywords: patents, R&D, scientific and market-oriented sources of knowledge, substitutability, complementarity.

JEL: O31, O32, L10

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† **Address**: KU Leuven, department of Managerial Economics, Strategy and Innovation, Naamsestraat 69, 3000 Leuven, Belgium; email: csc@cebr.dk

1 Introduction

Basic science has long been understood to be a major input of technological progress and economic growth. For instance, Jaffe (1989) and Adams (1990) find that basic science, public expenditures or fundamental knowledge are crucial determinants of innovation by private corporations and economic growth. The uncertainty associated with Research and Development (R&D) activities and the growing complexity of the knowledge creation process has led many firms to acquire technologies outside their boundaries to complement their own R&D efforts (Cassiman and Veugelers, 2006). However, very little is known about the channels through which different sources of knowledge affect a firm's performance. This is in large part due to the fact that a firm or an invention's linkages to external sources of knowledge do not always leave a publicly accessible "paper trail". In this respect, recent research has used patents and the references to the non-patent literature (NPL) they contain in order to analyze the effect of an invention or firm's science linkage on innovative performances, generally measured by forward citations to a focal patent or firm. For example Cassiman et al. (2008) in an analysis at the patent level, find no effect of NPL references on forward citations, but find that the firm's science linkage has more explanatory power for patent quality. In the same vein, Nagaoka (2007) finds that firms having a high number of citations to scientific publications also have portfolios of patents of higher average quality.

This paper builds on the latter stream of research by analyzing the effect of scientific knowledge at the patent level. Patent data are supplemented with the results from a survey which enables me to use more direct measures of a patent's reliance to science and other sources of knowledge as well as a more precise measure of the value of patents. The paper has two objectives. The first more general objective is to identify to what extent scientific sources of knowledge affect the value of patented inventions. The second more specific motivation is to study the synergies between scientific sources of knowledge and private, market-based sources of knowledge. I argue that the type of knowledge sourced can determine the private value of an invention. The knowledge utilized for the invention is characterized on two dimensions, its scientific orientation and its linkage with market-oriented actors. More specifically, I will test wether "scientific" and "private", market oriented sources of knowledge are complements or substitutes in the value of inventions. On the one hand, using private sources of knowledge to complement scientific linkages could ease the market acceptance of the innovation. But on the other hand, existing studies show that there can be diseconomies in pursuing multiple R&D strategies. I will apply the test of supermodularity/submodularity to answer the question whether or not firms gain from using both sources of knowledge simultaneously.

The paper is organized as follows. The next Section gives a background to the topic. Section 3 describes the testing framework. Section 4 describes the data. Section 5 presents the results and Section 6 concludes.

2 Background and hypotheses

The positive impact of basic research on industrial performance has gained a wide acceptance and became of great interest to economists and policy makers alike. The seminal work of e.g. Griliches (1984), Jaffe (1989) or Adams (1990) have underlined the contribution of scientific activities on social welfare. Since then, a growing literature on these industry-science links has complemented the beforementioned studies (see for example Lichtenberg, 2003 or Toole, 2007). This literature shows that firms try to appropriate and exploit the knowledge created in academia in order to create path-breaking innovations and get a head start in emerging markets.

At the same time, firms will seek to tap knowledge from actors that are close to the market they wish to exploit in order to reduce the uncertainty associated with innovative activities, source new ideas, or improve the quality of their products. These market-related actors can be users or customers (Von Hippel, 1988), direct competitors (Das and Teng, 2000) or suppliers (Hagedoorn, 1993).

External knowledge acquisition is vital to firms in the context of rapid technological change. For example, firms in the biotechnology sector cannot rely on their internal capabilities solely and have to tap knowledge outside their boundaries in order to be successful in innovation (Powell et al., 1996). Even the early literature on technological change asserts that external sources of knowledge are vital for innovation (Allen and Cohen, 1969). This leads us to the first hypothesis:

H1: A firm will be more likely to create valuable inventions if it looks to external sources of knowledge.

However, little is known about the interplay between these scientific and market-related sources of knowledge. Instead of studying the effect of scientific knowledge in isolation, I will study the interaction of scientific knowledge with other potential sources of knowledge that may affect a firm's performance. In other words, I will test whether scientific and market-oriented sources of knowledge are complements or substitutes in the value of patents. An invention's science linkage can take multiple forms, ranging from formal collaboration with universities or faculty consulting (Jensen et al., 2007), to informal collaboration such as attendance at university seminars or the use of scientific publications by the inventors. Similarly, market-based knowledge acquisition can take the form of formal or informal collaboration or communications with market-oriented actors such as competitors, suppliers, or customers.

The concept of absorptive capacity introduced by Cohen and Levinthal (1989) and defined as the ability of a firm to recognize, assimilate and utilize external knowledge goes into that direction. Absorptive capacity will enable a firm to effectively integrate external knowledge and reap the benefits from its exploitation. For example, Nerkar and Roberts (2004) find that firms that engage into new product commercialization also need a strong product market orientation, what they call "a general combinative capability" (a concept similar to absorptive capacity) in order to achieve a positive result in terms of sales. However, as shown by the literature, drawing knowledge from different contexts creates limitation in absorptive capacity. For example, there is ample evidence that knowledge spillovers (measured through patent citations) tend to be localized (Jaffe et al., 1993; Henderson et al., 1998) and that firms face difficulties when trying to source knowledge across national boundaries. Moreover, Phene et al. (2006) find that simultaneous exploitation of technologically and geographically distant knowledge inputs by firms does not generate breakthrough innovations, as measured by the top 2% most cited patents. Another example can be found in the literature on R&D collaboration, that shows that some firms suffer from diseconomies in pursuing multiple cooperation strategies (Belderbos et al., 2006). Other examples are Cassiman and Veugelers (2007) who find a substitutive relationship between disembodied and embodied technology acquisition for small firms (and an independent relationship for large firms) and Singh (2008) who finds that geographic dispersion of a firm's R&D activities is negatively correlated with the average value of innovations, coming from the fact that firms face difficulties in integrating knowledge across multiple locations.

Nerkar and Roberts (2004) found that firms that develop experience in their technological and product-market domains will be more successful in developing new products. This is suggestive of the existence of complementarities between these *internal* sources of knowledge (the experience accumulated within a firm's boundaries). However, the literature surveyed tends to reveal that using *external* knowledge from distant sources and contexts can be "subadditive", since it may lead to information overload and diseconomies of scale. These harmful consequences may occur as a firm tries to manage assimilation and integration of disparate items of external knowledge from distant technological contexts. Basic R&D reliance and market-relatedness can indeed be viewed as being "distant" external sources, since scientific knowledge sourcing aims at exploring novel technologies, whereas market-related sources of knowledge aim at exploring familiar technologies. This leads to the second hypothesis:

H2: Scientific and market-related sources of knowledge are substitutes in the value of innovations.

3 External knowledge acquisition and the test for substitutability/complementarity

The study of complementarity/substitutability can be traced back to the theory of supermodularity/submodularity (Topiks, 1978; Milgrom and Roberts, 1990). The first empirical methodology in this paper follows the "production function" approach, that has been shown to be more appropriate than the "adoption approach" that relies on correlation of residuals from reduced-form equations (Arora, 1994; Athey and Stern, 1998).

Two activities are complementary (resp. substitutable) if increasing the utilization of one of them increases (resp. decreases) the returns from doing more of the remaining activity. In a differentiable framework, complementarity requires the cross-partial derivatives of the innovation function to be positive and substitutability requires them to be negative. Suppose there are two potential sources of knowledge, D_1 and D_2 and an innovation function v that measures the value of a focal patent that an inventor (or an applicant) seeks to maximize. Each source of knowledge can be used by the inventor during the invention process ($D_s = 1$) or not ($D_s = 0$), with $s \in \{1, 2\}$. If the innovation strategies were measured by continuous variables, supermodularity (resp. submodularity) would require the cross-partial derivative of v with respect to D_1 and D_2 to be positive (resp. negative). In the present case, the external sourcing strategies are measured by dummy variables. Therefore, the definition of supermodularity and submodularity can be expressed in terms of unit differences. The following definition draws from Cassiman and Veugelers (2006):

The function $v_i(D_{1i}, D_{2i}, X_i)$ where X is a vector of controls is supermodular and D_1 and D_2 are complements if:

$$v_i(1, 1, X) - v_i(0, 1, X) \geq v_i(1, 0, X) - v_i(0, 0, X) \quad (1)$$

i.e., using a source of knowledge while the other source of knowledge is already being used has a higher incremental effect on performance than using a source of knowledge in isolation.

Similarly, the function $v_i(D_{1i}, D_{2i}, X)$ is submodular and D_1 and D_2 are substitutes if:

$$v_i(1,1,X) - v_i(0,1,X) \leq v_i(1,0,X) - v_i(0,0,X) \tag{2}$$

In order to test for the existence of substitutability or complementarity between scientific and private sources of knowledge, I estimate the innovation function with the following specification:

$$v_i = \alpha + \delta X_i + \beta_{10} S_{10i} + \beta_{01} S_{01i} + \beta_{11} S_{11i} + \varepsilon_i \tag{3}$$

where the S_{si} are exclusive dummies indicating the sources of knowledge chosen by the inventor of patent i, $\forall s \in \{1,2\}$ and X is a vector of control variables. More specifically, the four dummies represent the different innovation strategies: an inventor can use *scientific* knowledge only S_{10i}, *private* knowledge only S_{01i}, both S_{11i} or none of them S_{00i}. The dummy S_{00i} is normalized to zero in order to include a constant. thus, the complementarity test between both sources of knowledge is:

$$\beta_{11} \mathrel{\substack{\geq \\ \leq}} \beta_{01} + \beta_{10} \tag{4}$$

4 Data

4.1 Sample

The data was compiled from the so-called "PatVal" survey for Denmark, that contains information on 495 patents granted by the European Patent Office (EPO), with priority dates between 1993 and 1997 and in which at least one of the inventor resides in Denmark. The PatVal project is a European-wide survey of inventors, which primary aim was to assess the economic value of European patents, by asking questions related to the personal characteristics of one of the inventors listed in the selected patents. A summary of the key findings of the Danish PatVal survey can be found in Kaiser (2006). Giuri et al. (2007) provide a summary of the PatVal survey for six other European countries.[1]

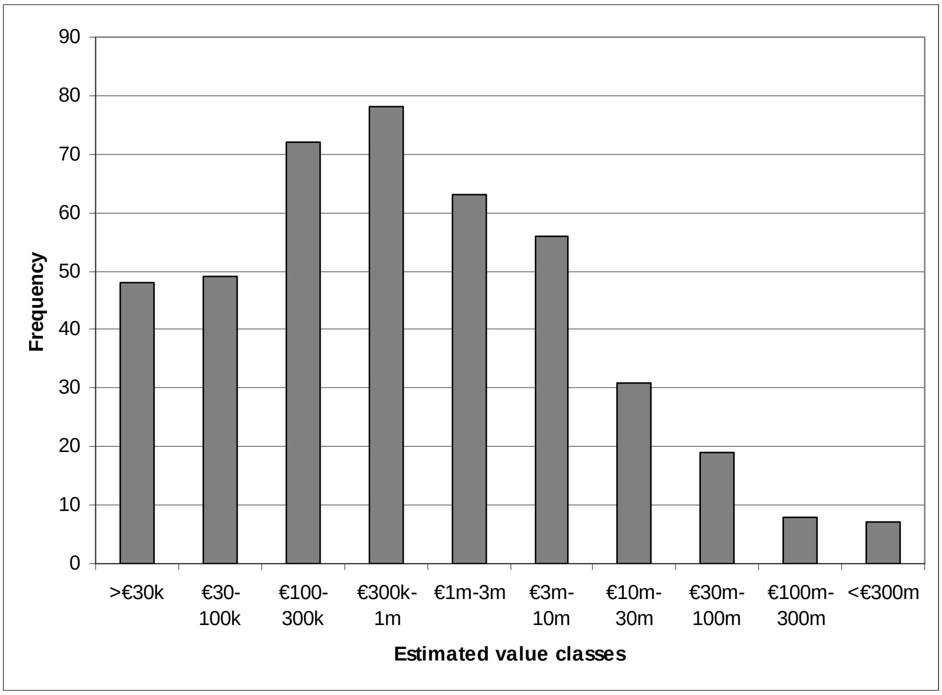
4.2 Dependent variables

The dependent variable quantifies the monetary value of the patent as estimated by the inventor. More precisely, the **present value of the patent** is based on the inventor's answer to the question *"Suppose that on the day in which this patent was granted, the applicant had all the information of the value of the patent that is available today. In case a potential competitor of the applicant was interested in buying the patent, what would be the minimum price the applicant should demand?"*. A set of ten interval responses was offered to the respondent: less than €30.000, €30.000-100.000, €100.000-300.000, €300.000-1 million, €1-3 million, €3-10 million, €10-30million, €30-100 million, €100-300 million, more than €300 million. Figure 1 shows the distribution of the value intervals which exhibits the usual skewness of patent values.

The robustness of this indicator is discussed in Gambardella et al. (2006) who validate this variable by comparing it with common alternative indicators of patent values, e.g. the number of forward, citations, the number of backward citations, the number of claims and the family size of the patent. Moreover, a similar type of measure has been used and validated in different studies in the past (see e.g. Harhoff et al, 1999). Using this indicator provides with a more direct measure of the monetary value of a patent compared to traditional value correlates. For comparison, patent renewal data have been used to estimate the lower bound of patent values (Pakes, 1986). Using this methodology, Deng (2007) reports that the avareage patent at the EPO is worth (at least) $131,857 in Germany, $51,589 in France and $31,798 in the

[1] France, Germany, Italy, the Netherlands, Spain and the United Kingdom.

Figure 1: Patent value classes



UK.[2][3]

4.3 Explanatory variables

To characterize patents for which **scientific sources of knowledge** was used, a dummy variable was created that indicates whether the inventors used university laboratories and faculty, public research institutes or scientific literature as a source of knowledge for the research that led to the patented

[2] The patents considered were granted between 1980-1985; all amounts are given in 2000 US Dollars and are taken from Table 4 in Deng (2007). It should be noted that these estimations only include the renewal fees paid in the given national patent offices and exclude application fees paid at the EPO and fees paid in other states designated in the application. Therefore the actual average patent value can be expected to be much higher.

[3] In addition, notice that the companie TOMO OCEAN that auctions patents publicly, reports average sale prices ranging between $305,250 and $578,607 per patents in the auctions held in 2007 and 2008, which is in the same order of magnitude than the patent values resulting from the survey. See http://www.oceantomo.com

invention. Similarly, inventors can use **market sources of knowledge**. This dummy was created if the inventors claimed to have used customers or product users, suppliers or competitors as a source of knowledge. From these two dummies, four exclusive categories were created, for patents in which none of the sources of knowledge was used (S_{00}); inventions for which only scientific information was used (S_{10}); inventions for which only market based information was used (S_{01}); and inventions that combine both scientific and market knowledge (S_{11}). These variables are summarized in Table 1.

For comparison, only 9% of the patents in the sample contain at least one non-patent reference, which confirms the presumption that this indicator underestimates the scientific linkage of patented invention.

In the remainder of the analysis, the disaggregated categories will not be used since it would give too many cases to consider, given that we have to create an exclusive dummy for each possible combination of sources of knowledge used[4]. Thus I will only focus on the two broader categories: scientific and market sources of knowledge. The correlation matrix at the right of Table 1 shows that there are strong correlations among the subcategories, which suggests that they can be aggregated.

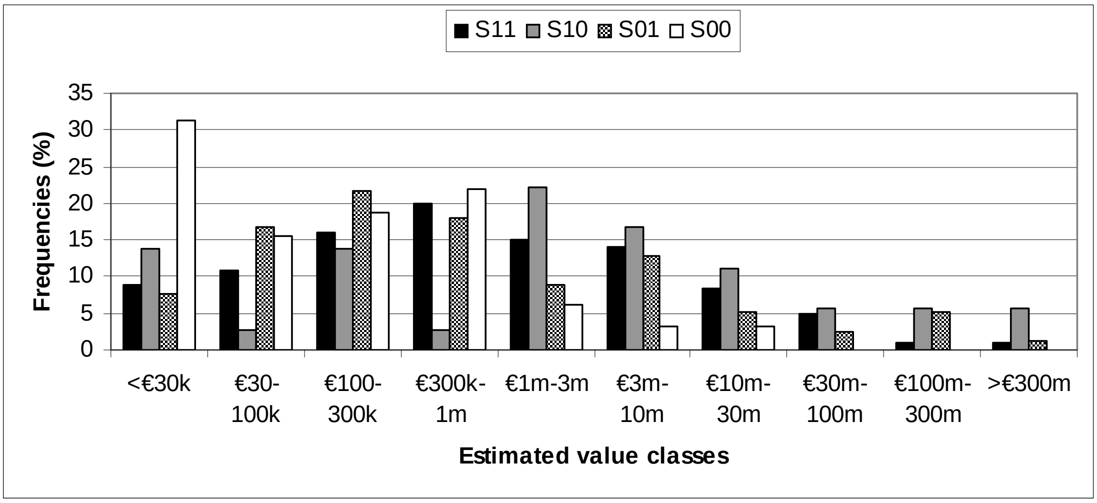
Table 1: descriptive statistics (1)

Sources of knowledge	N	Mean	Std. Dev.	Min	Max	1	1.1	1.2	1.3	2	2.1	2.2	2.3
Non-exclusive dummies													
1. Scientific sources of knowledge	410	69.02%	0.463	0	1	1							
1.1 Universities	430	34.19%	0.475	0	1		1						
1.2 Public research institutes	426	23.00%	0.421	0	1		0.333	1					
1.3. Scientific publications	445	69.21%	0.462	0	1		0.431	0.244	1				
2. Market sources of knowledge	416	81.97%	0.385	0	1	0.134	0.053	0.131	0.074	1			
2.1 Customers, product users	458	74.45%	0.437	0	1	-0.050	-0.095	0.094	-0.154		1		
2.2 Suppliers	431	45.94%	0.499	0	1	0.079	0.073	0.240	0.026		0.332	1	
2.3 Competitors	437	57.67%	0.495	0	1	0.086	0.033	0.179	0.068		0.308	0.199	1
Exclusive dummies													
S11	396	58.08%	0.494	0	1								
S10	396	10.35%	0.305	0	1								
S01	396	23.23%	0.423	0	1								
S00	396	8.33%	0.277	0	1								

Figure 2 shows the distribution of patent value classes according to the external sourcing strategy. It reveals that inventions for which none of the

[4] If n is the number of categories, we need to create 2^n exclusive dummies.

Figure 2: Patent value classes by innovation strategy



external sourcing strategy was used (S_{00}) are more likely to be found in the lower tail of the patent value distribution. On the other hand, inventions that benefited from at least one of the external sources of knowledge are more frequent in the right tail of the distribution, suggesting that external knowledge sourcing is beneficial to a focal invention. However, it seems that the utilization of scientific knowledge only (S_{10}) leads to patents of higher value than the joint adoption strategy (S_{11}), which is suggestive of a substitutive relationship.

4.4 Control variables

Throughout the analysis, the **monetary cost** of the invention will controlled for. The questionnaire asked for the estimated amount spent for the invention that led to the patented invention. This is an important variable, since large scale projects are likely to lead to more valuable patents. Gambardella et al. (2006) already show that there is a systematic correlation between the scale of resources invested in the project and the value of its output. In addition, three dummies indicating whether any of the applicant of the patent is a **small firm** (with less then 100 employees), a **medium firm** (with a number of employees between 100 and 250) or a **large firm** (more than 250 employees).[5] Firm size might affect the "quality" of the invention, but the sign of this effect is not obvious. On the one hand, small firms might suffer from deficiencies in economies of scope and/or scale compared to larger corporations and on the other hand they may produce innovations of higher "value" because they have a reduced bureaucratic burden in comparison to large companies (Acs and Audretsch, 1987; Cassiman and Veugelers, 2006).

In addition, the analysis will control for year and technology fixed effects. Patent values might be influenced by variations over time, due to changing technological opportunities over the years, and technology areas due to the fact that inventions in some technology areas are intrisically more valuable. For these reasons, I include dummies for different **application years** and six **technology class** dummies using the so called OST-INPI-FISI classification, provided by the "Office des Sciences et Techniques" (OST), the French Patent Office (INPI) and the Fraunhofer ISI Institute, which is based on a concordance with the (primary) International Patent Classification (IPC) assignment.

[5] There was actually no observation with a university-owned patent in the survey used in this paper. In Schneider (2007), I show that there were only eight patents applied for by Danish universities or public institutions at the EPO in the period 1978-1998.

Table 2: descriptive statistics (2)

Variable	N	Mean	Std. Dev.	Min	Max
Controls					
Estimated cost/1.000.000	491	5.495	112.830	0	2500
Small firm (<100 employees)	495	24.24%	0.429	0	1
Medium firm (100<employees<250)	495	9.70%	0.296	0	1
Large firm (>250 employees)	495	68.08%	0.467	0	1
Application years					
1993	495	2.020%	0.141	0	1
1994	495	25.657%	0.437	0	1
1995	495	19.798%	0.399	0	1
1996	495	18.990%	0.393	0	1
1997	495	22.828%	0.420	0	1
1998	495	10.707%	0.310	0	1
Technology classes					
Electricity-electronics	495	8.081%	0.273	0	1
Instruments	495	11.313%	0.317	0	1
Chemicals, pharmaceuticals	495	24.646%	0.431	0	1
Process engeneering	495	18.990%	0.393	0	1
Mechanical engeneering	495	26.667%	0.443	0	1
Others	495	10.303%	0.304	0	1

5 Results

Since the dependent variable is interval coded, the model is estimated using an ordered probit with known thresholds (or interval regression). The interval boundaries are log-transformed to account for the skewness of the patent values distribution (Wooldridge, 2002). The lowest boundary of the first interval is treated as censored, since it is a corner solution in the firm's optimization program. Correspondingly, the upper bound of the last interval is also treated as censored, since it is set to $+\infty$.

The first set of results are presented in Table 4. The estimation results contain the two non-exclusive dummies and the controls to provide a baseline specification. The results suggest that large scale projects, as measured by the cost of the invention, are more likely to generate patent of high value. Similarly, medium and large sized firms are more successful in turning their invention into valuable assets. This result goes in the direction of the Schumpeterian argument that large firms might be more capable of producing high quality technologies due to scale economies and advantages in accessing upfront knowledge in the market. The significance of the two non-exclusive dummies suggest that they convey little information as such, except that the coefficient for scientific sources of knowledge is much larger in magnitude than the coefficient on market-oriented sources of knowledge.

Table 4: Estimation results (1) - ordered probit with known thresholds

	Coef.	S.D.	Coef.	S.D.	Coef.	S.D.
Scientific sources of knowledge					0.418	0.329
Market sources of knowledge					0.114	0.359
log(cost)	0.159***	0.040	0.159***	0.032	0.149***	0.037
Large firm			2.001**	0.849	2.176***	0.903
Medium firm			1.970**	0.890	2.168**	0.942
Small firm			1.159	0.826	1.333	0.874
Application years	Included		Included		Included	
Technology classes	Included		Included		Included	
Constant	-0.473	0.990	-2.362	1.249	-2.332*	1.424
sigma	2.534***	0.115	2.499***	0.096	2.485***	0.105
Log-likelihood	-889.828		-885.188		-717.810	
Number of observations	429				349	
	48 left cens., 7 right cens.				39 left cens., 5 right cens.	

The second set of results include the exclusive combinations of scientific and market-oriented knowledge sourcing decisions. Overall the signs of the controls do not change and their magnitude does not differ very much.

First, notice that inventions building on external sources of knowledge are, on average, more valuable than inventions building on internal knowledge solely. This validates our first hypothesis, implying that firms sourcing knowledge outside their boundaries produce innovations of higher value.

Turning to the question of complementarity versus substitutability, the results show that the coefficient on S_{10} is the largest in magnitude, suggesting that patents with a scientific linkage only are of higher value on average. Overall, the coefficients on scientific knowledge sourcing only (S_{10}) and market-oriented knowledge sourcing only (S_{01}) are higher than the coefficient of the joint strategies adoption (S_{11}) suggesting that both practices are subadditive rather than complements. Inequality (4) is directly tested using a one-sided Chi2 test. The test, shown at the bottom of Table 5, confirms that both practices are indeed substitutes in the value of patents. This result confirms the second hypothesis and suggests that simultaneous exploitation of scientific and market-oriented sources of knowledge results in suboptimal performance in terms of the value of the resulting patent. This means that there might be significant obstacles to managing several sources of knowledge simultaneously.

Table 5: Estimation results (2) - ordered probit with known thresholds

	Coef.	S.D.	Coef.	S.D.
S11	1.567***	0.540	1.533***	0.534
S10	2.483***	0.672	2.461***	0.665
S01	1.603***	0.560	1.612***	0.555
log(cost)	0.129***	0.037	0.132***	0.037
Large firm			2.094**	0.888
Medium firm			1.924**	0.929
Small firm			1.192	0.861
Application years	Included		Included	
Technology classes	Included		Included	
Constant	-1.4236	1.185	-3.423**	1.434
sigma	2.479***	0.105	2.441***	0.103
Test of no substituability:				
Chi2 (p-value)	9.48 (0.001)		7.72 (0.002)	
Log-likelihood	-716.806		-711.479	
Number of observations	349			
	39 left censored, 5 right censored			

6 Conclusion

This paper analyzes the relationship between two alternative sources of knowledge acquisition. The inventors can use scientific sources of knowledge, stemming from universities, public research institutions or scientific publications. On the other hand, inventors can use sources of knowledge that are close to the market which can help enhancing the market acceptance of the product (or the technology). Using the testing framework developed in Athey and Stern (1998) and Cassiman and Veugelers (2006, 2007), I examine the nature of the relationship between these two types of knowledge acquisition. In addition, I also focus on exogenous sources of variation that affect the perceived relationship.

The first result shows that inventions using scientific sources of knowledge result in patent of higher monetary value. The test carried out in the paper reveals a substitutive relationship between the two sources of knowledge, suggesting that simultaneous exploitation of different knowledge inputs is "subadditive" since inventors would have to manage assimilation and integration of disparate items of knowledge from multiple technology contexts. Thus, firms are able to reap higher benefits by using one source of knowledge only.

However, this does not mean that these sources of knowledge should never be used simultaneously. Relying on basic science solely can provide the basis for breakthrough innovations, but the outcome is associated with high uncertainty. In contrast, market-relatedness yields immediate and more likely returns, but increases the risk of the firm falling into a "familiarity trap" (Ahuja and Lampert, 2001) by building on familiar knowledge. Therefore, scientific knowledge acquisition, that is presumably directed toward radical or explorative innovations would require complementary inputs to enhance market acceptance and diffusion and would therefore reduce the uncertainty associated with radical, innovations. At the same time, the joint utilization of both sources of knowledge can break a firm's path dependency and prevent it from falling into a familiarity trap.

One solution to overcome this subadditive relationship would be to use technological "gatekeepers", as suggested in the early literature by Allen (1977) to improve the external sourcing startegy.

Given the lack of strong theoretical priors, future research should be directed toward more theoretical work to help explaining the choice and exploitation of different knowledge inputs.

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