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THE EFFECT OF RARITY AND UNCERTAINTY ON INNOVATION VALUE

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Abstract

This paper addresses the core notions of the Resource Based View, that rarity provides superior performance. We examine the limits of rarity as a driver of performance in the process of innovation. We also claim that uncertainty affects this process, both directly and moderating the effect of rarity.
Using patent data relative to hydrocracking – a mature technology experiencing periods of stable and unpredictable development – we find that rarity has a U-shaped effect on innovation value, as both rare and non-rare inventions are valuable. Uncertainty has an inverted U-shaped effect on innovation value, as in conditions of low uncertainty incremental innovation tends to prevail, while high uncertainty leads to imitation of successful practices. Low, but not high, uncertainty moderates the relationship between rarity and innovation value.

Introduction

A vibrant scholarly debate has emphasized the challenges in using the Resource Based View (Wernerfelt 1984; Barney 1991) as a theoretical approach in strategic management research (Priem and Butler 2001a; Priem and Butler 2001b; Hoopes, Madsen et al. 2003; Lockett, Thompson et al. 2009; Kraaijenbrink, Spender et al. 2010; Wernerfelt 2013) focusing, in particular, on the shortcomings of the concept of competitive advantage (Powell 2001); on the indeterminateness of the notion of value and resource (Priem and Butler 2001a; Priem and Butler 2001b); and on the fact the applicability of theory is too limited (Miller 2003; Gibbert 2006; Levitas and Ndofor 2006). Recently, one of the core concepts of the Resource Based View, namely the notion that rarity of a resource or a capability contributes to a firm's performance, has been questioned and, for the first times, empirically tested. It has been pointed out that firms benefit from rare *combinations* – rather than rare individual resources and capabilities (Kor and Leblebici 2005; Teece 2007; Newbert 2008), and that rarity of dynamic, but not ordinary capabilities matters for firm performance (Drnevich and Kriauciunas 2011). These contributions emphasize the need for a better conceptualization as well as for systematic empirical evidence of the theorized propositions of the Resource Based View.

We take part in this debate by investigating under what conditions *rare* and *non-rare* capabilities contribute to firm performance. In line with Drnevich and Kriauciunas (2011), we qualify a capability as "rare" when it is developed and used only by one or few firms in an industry. Furthermore, we analyze the role of uncertainty as a main moderating factor in regards to the value captured from either rare or non-rare capabilities. Uncertainty has been highlighted as an important theoretical concept in the Resource Based framework (Foss and Knudsen 2003), but our knowledge of its impact is still limited (eg. Schmidt and Keil 2013).

In this paper, we deepen our understanding of the concept of resource value by examining a crucial function for sustainable competitive advantage: innovation management. We explore the relationship among the value of an invention, the rarity of the technological capabilities upon which they build and the uncertainty surrounding that technology. It is well known that not all inventions are patented, and a single invention may give rise to several patents dealing with each of its components (Arundel and Kabla 1998; Jaffe 2000; Zeebroeck 2011). Anyhow, patents are important assets of firms and they play a central role in technology management, and scholars and practitioners are increasing interested in measuring their value (Ernst 2003; Gambardella 2013).

A patent is at the same time an asset for a firm, and an expression of its technological capabilities (Trajtenberg 1990). Within the theoretical framework offered by the Resource Based View (eg. Wernerfelt 1984; Barney 1991) it has been proposed that firms not only acquire, but also develop resources internally (Dierickx and Cool 1989): it is then possible to argue that firms that develop unique technological capabilities and protect them by means of a patent – a legal tool that protect them from imitation – may achieve a competitive advantage. This theoretical approach suggests an association between the rarity of a technological capability and the contribution to performance of the patented invention that exploits that capability. However, we argue that not only rare technological capabilities for innovations are valuable and may be a source of competitive advantage: innovations that are highly related to other complementary innovations are likely to build on non-rare technological capabilities, why non-rare capabilities also become valuable.

Our study moves one step further, suggesting that the value of a technological capability is not fully explained by its rarity (or non-rarity), but is contingent on the uncertainty of the technological environment. The *uncertainty* characterizing a technology or a set of interrelated technologies depends on the dynamics of demand (Fontana and Guerzoni 2008), the stage of development of a technology and the existence of competing technologies (Ragatz, Handfield et al. 2002). Uncertainty tends to increase the value of more non-rare technologies, particularly as uncertainty increases with technological complexity (Tushman and Rosenkopf 1992). In fact, an uncertainty increases transactions costs that ultimately increases operational costs (Artz and Brush 2000).

We suggest that companies achieve a competitive advantage when they develop technological capabilities that are consistent with the degree of technological uncertainty of the environment in which they compete. We take the empirical case of hydrocracking to explore these issues. Hydrocracking is a mature technology widely used as a part of the oil refinery process to transform crude oil into high value petroleum products. Innovations in hydrocracking are based on both rare and non-rare combinations of technological capabilities, making it an ideal setting to explore the effects of technological rarity. Furthermore, the degree of uncertainty surrounding this technology fluctuated, in particular after 1970.

The findings of our study show that, consistently with expectations, both rare and non-rare technological capabilities result in above normal returns in terms of patent value; and that the relationship between uncertainty and value is inverted U-shaped. The benefits from increasing uncertainty are subject to negative returns, indicating that there is a point where higher levels of uncertainty become unfavorable. Finally we find that low uncertainty has a negative moderating effect on the effect of rarity on patent value.

This paper contributes to the ongoing debate on the academic standing of the Resource Based View, providing an empirical test of its core propositions that better specifies to what extent of rare resources and capabilities contribute to competitive advantage; furthermore, it addresses a central issue in Management of Innovation, i.e. generation of inventions, providing insights on the internal and external conditions that support the invention process. These results provide managers with precious information about how to effectively organize Research & Development (R&D) activities, as they characterize the features of the capabilities and of the environment that drive innovation value.

The remains of this paper is structured as follows; first we introduce key theoretical concepts and build our hypotheses, this is followed by an overview of the data and methodology applied, presentation of our empirical findings and rounding up with a discussion of the results.

Effects of rarity and uncertainty on individual innovations value

Rarity of competencies and value of innovations

The Resource-Based View (Penrose 1959; Wernerfelt 1984; Barney 1991; Teece, Pisano et al. 1997) (Hamel and Prahalad 1993; Teece, Rumelt et al. 1994) has affirmed itself as one of the leading theoretical frameworks in Strategic Management (Rouse and Daellenbach 2002; Newbert 2008); providing a powerful framework to relate the process of accumulation of technological capabilities to the value of a technological innovation. This theoretical approach argues that a sustainable competitive advantage is conveyed by bundles of valuable, rare, inimitable, and/or non-substitutable resources and capabilities. If a resource or competence yields the potential to enable a firm to reduce costs and/or respond to environmental opportunities and threats, it is valuable, and to the extent that a firm is able to effectively deploy such a resource or capability, it will attain a competitive advantage (Barney 1991). According to this perspective, patents can be considered as competitive advantage-enabling asset, as they protect inventions from imitation. The resource-based perspective thus helps our understanding of how the internal environment of the firm affects the process of innovation, and of how the value of resources and competencies is associated to the fact of being 'rare'.

The idea that invention is the result of a process of recombination of knowledge about the components of a product or the reconfiguration of their architecture is well established in the literature on management of technology (Henderson and Clark 1990; Fleming and Sorenson 2004). Experience in deepening the knowledge of a specific technological component refers to the technological capability of a firm, which is distinct from the architectural capability consisting in combining different technology areas. Improvements of the knowledge of the components, as well as their original recombination are sources of technological innovation (Makri, Hitt et al. 2010).

It has been argued that the rarity of a combination of capabilities related to a specific functional area is a driver of competitive advantage (Newbert 2008), and studies on technological capabilities have shown that their rarity is associated to with being able to produce innovations that are rare to the market (Danneels 2002; Miller 2003; Danneels 2007).

However, also non-rare capabilities contribute to competitive advantage. It is the case of the capabilities that all firms in an industry should possess in order to compete effectively (Winter 2003) or those that represent an effective way to deal with common technical problems, and for this reason they are adopted quite homogeneously by firms in an industry (Eisenhardt and Martin 2000). Broad diffusion of a capability generates a shared knowledge base that firms in an industry can exploit by means of imitation and incremental development with an external-learning advantage, as existence of a shared pool of knowledge they can reduce the costs related to the use of a capability by means of imitation and incremental development (Aghion and Howitt 1998). Under such conditions, the cost of using a common resource is lower than that necessary to develop a unique resource or capability internally (Greve 2009; Drnevich and Kriauciunas 2011).

With specific regard to management of innovation, non-rare capabilities provide two additional sources of value. First, a rare capability indicates a discontinuity with the existing technological base of an industry. This may be a source of competitive advantage, but, at the same time, reliance on rare technological capabilities limits the possibilities for a firm to exploit the advantages of complementary technologies thus limiting the strategic options for the innovating firm; on the other hand, a non-rare capability may fit better with the existing capability base of an innovating firm, thus carrying more value than a rare one (Butler 1988; Makri, Hitt et al. 2010; Wu, Wan et al. 2013). Second, the learning literature emphasizes that deepening the knowledge of non-rare technologies activates learning processes so that such knowledge reaches the level to be a strategic resource (Argote 1993; Levinthal and Wu 2010).

For these reasons, the ability to generate valuable innovations may be provided to the firm by either developing technological competencies that are widespread in the industry and have a broader scope of application, or creating rare technological competencies that may sustain the generation of discontinuous innovations. We consider less rewarding for innovation an "intermediate" strategy, consisting in developing capabilities that are neither rare nor non-rare.

For this reason we expect

Hypothesis 1: *The relationship between the value of an innovation and rarity is curvilinear and takes an U-shape.*

Uncertainty and innovations value

Environmental dynamics affect a firm's competence base, as they determine the possibility of a competence to be deployed for generating innovation. Notably, substantial changes in the technological environment may make a competence obsolete, eroding its value (Danneels 2002). While rare technological capabilities can generate discontinuous innovations, and thus they are valuable assets for a firm, they tend to be associated with a higher degree of environmental uncertainty than non-rare technological capabilities (Fleming 2001). The process of innovation is influenced by uncertainty and serendipity, so that firms cannot predict whether their R&D effort will be successful in terms of generating an innovation, or successful in terms of the most efficient strategy to address a research puzzle (Ahuja, Lampert et al. 2008), and the investment in complementary resources needed to bring an invention to commercialization (Reitzig 2006). Furthermore, it is well known that the degree of uncertainty surrounding a given technology varies across the various stages of its development (Anderson and Tushman 1990). Environmental uncertainty refers to the predictability of the demand for the final and intermediate goods the technology will be incorporated (Sorenson 2000), as well as the pattern of development of technology and the resources required for its elaboration (Makadok and Barney 2001) and the combined effect of market and technology forces (Souder, Sherman et al. 1998).

When a firm can easily predict the development of technologies and markets, decision-making and organization of R&D are relatively simple, as the interpretation of consumers' preferences and competitors' moves requires a much simpler computational effort. A clear picture of the environmental dynamics permits a firm to focus its R&D efforts in the development of the technological capabilities that are likely to drive to a competitive advantage.

However, in conditions of low environmental uncertainty there is less room for differentiation since all firms have shared expectations of technological dynamics. Furthermore, low uncertainty environments can be dominated by incremental, technical change, whereby the opportunity for radical innovation is low (Tushman and Rosenkopf 1992).

In conditions of high environmental uncertainty, firms establish more sophisticated R&D organizations, with stronger inter-functional integration (Artz and Brush 2000). This allows firms to experiment novel approaches to R&D, either increasing or reducing their investment and commitment to a specific technology trajectory. In conditions in which it is difficult to assess the relative value of different technological combinations (Ragatz, Handfield et al. 2002), firms tend not to follow optimization criteria to define their R&D strategy, but rather base their decision-making on heuristics (Bingham, Eisenhardt et al. 2007; Bingham and Haleblian 2012). In an uncertain environment firms tend to imitate innovative decision as well as decision-making processes from successful firms, so that innovation models diffuse fast in the industry (Dimaggio and Powell 1983; Davis 1991; Westphal, Seidel et al. 2001; Ahuja, Lampert et al. 2008).

These two opposite forces suggest that an optimal environment for creating valuable innovations is located between high and low environmental uncertainty.

For this reason we expect

Hypothesis 2: The relationship between the value of an innovation and environmental uncertainty is curvilinear and takes an inverted U-shape.

This paper aims to shed new light on the effect of environmental uncertainty on the relationship between the rarity of the technological capabilities on which an innovation builds on, and its value. We expect that the possibility for a firm to extract a valuable innovation out of either a rare or non-rare combination of technological capabilities is contingent to the uncertainty characterizing the pattern of evolution of the technology.

In conditions of high uncertainty, irreversible investments in the development of technological capabilities present a high opportunity cost. In fact, an investment in capabilities that are functional to pursue a given technological trajectory may lose its value if the industry shifts on an alternative technological trajectory. For this reason, firms evaluate their commitment to a specific technological pattern comparing alternative options; this may lead firms to delay their investment decision as well as to invest in capabilities that can be exploited in different technological domains (McGrath 1997; Leiblein 2003). In these environmental conditions, firms developing non-rare technological capabilities seem to have an advantage in adapting to alternative future scenarios, as long as these capabilities entail a higher degree of generality. However, these environmental conditions strengthen also the value of more rare capabilities: in fact, the future development of the technologies can make intensive use of a specific combination of technological competencies, which thus increase their relative value vis-à-vis alternative combinations of competencies. The actual value of competencies under high uncertainty is difficult to predict; however, it is possible to argue that rare competencies benefit from increases in uncertainty.

By contrast, under conditions of low uncertainty, innovation tends to be incremental along the dominant trajectory (Utterback and Abernathy 1975; Levinthal and Wu 2010). A clear competitive and technological map of the demand reduces the risks associated with the development of unique capabilities (Sorenson 2000) as well as the investment in non-rare capabilities. In these conditions, a broader range of technological capabilities becomes useful to generate innovations – not only those at the extremes of the distribution, i.e. those that are extremely unique or widespread in the industry.

For this reason we expect

Hypothesis 3a: The relationship between the value of an innovation and rarity is moderated by high uncertainty in such a way that the U-shape relationship is sharpened.

Hypothesis 3b: The relationship between the value of an innovation and rarity is moderated by low uncertainty in such a way that the U-shape relationship is flattened.

Data and Variables

This study draws upon a unique dataset consisting of all the patent applications within the *Hydrocracking* technology to explore the hypotheses presented above. We classify the patent applications in our dataset into the distinct technology areas present in the hydrocracking on the level of each innovation, using these as a representation of the applied research outcomes within the industry (Meyer 2000). Combinations of these classifications are used to indicate whether an innovation builds upon a combination of more than one technology area, hereby we can identify how rare a certain type of technological combination underlying an innovation is, at any point in time, within the industry.

The use of patent data to explore technology combinations has predominantly relied on the use of the international patent classification (IPC) codes to identify the technological scope of a patent, though prior studies have experienced some discrepancy in the measure (Lerner 1994; Harhoff, Scherer et al. 2003). This is caused in part by the IPC as patents are assigned codes by the individual patent examiner, and while the individual patent office follow a coherent classification scheme; regional differences have a significant impact on how a patent is classified (Harhoff, Scherer et al. 2003). This is supported by a prior study finding only a weak correlation between Standard Industrial Classification (SIC) and IPC codes, in addition to some technology areas being covered by different sections of the IPC (Cohen, Nelson et al. 2002). These issues become further apparent when taking into account that a single patent can be classified by multiple IPC codes, where a weak relation was found between IPC codes at the three- and four-digit level (Leydesdorff 2008). Therefore, in an effort to counter these issues, we offer an alternative to counting IPC classes to determine the technological scope of a patent. This is achieved through a novel approach where IPC codes are grouped according to their technological application through a qualitative process with the aid of a technical expert within the field. Through this process we identify three distinct technology areas, each associated with a group of IPC codes relevant to each distinct technology area. Each patent application in our sample is classified according to one or more of these technology areas. This process highlighted the deficiency of using IPC codes as an indicator of technological proximity due to IPC codes similar in the classification scheme can prove to be covering an alternative application or competing technology. Such issues are difficult to identify through quantitative methods, as to very different IPC codes often share the first seven of the nine digits in the IPC, making it difficult to positively identify technological proximity without the means of expert advice.

Hydrocracking is a technology covering the later stages of the oil refining process, utilizing a process of catalytic cracking to convert heavy hydrocarbons into higher added value, lower molecular weight compounds under hydrogen pressure (Billon and Bigeard 2001). Thereby this technology increases the value of refinery output through a conversion of lower value petroleum products, such as lubrication oils, into higher value products, such as jet fuel. While this is a mature technology originally developed in 1927 to hydrogenate coal distillates, the continued application of the technology in modern refineries ensures that the technology is continuously developed.

The hydrocracking technology has evolved over time in terms of innovation output, in Figure 1 we present the patents applied per year and the accumulated number of patents applied in the industry. In the graph showing the patent applied annually, it is clear that the industry has had its ups and downs, peaking in 1983 and 1998, and with lowest volume of patent applications in 1979, 1992 and 2006. These fluctuations make the industry a good match to investigate environmental uncertainty.

Insert Figure 1 about here

With expert aid, we identified three distinct technology areas within hydrocracking. Process technologies (which we name ‘A’) are primarily associated with how the process of hydrocracking is integrated into the overall refinery process, and therefore includes technologies concerning the flow of petroleum based liquids, including valves, pipes, and the associated controllers. Catalyst preparation (we name ‘B’) is concerned with the manufacturing process of the catalyst necessary for hydrocracking to take place. This includes both the manufacture of the carrier of the catalyst (the base to which the active component in the catalyst is applied) and the application of the active component onto the carrier in the manufacturing process. The area of feeds and products (we name ‘C’) is concerned with the chemical nature of the raw materials of the refineries (feeds), and the chemical reactions that change specific feeds into specific products. These three technology areas find application both alone and in combination with each other[1], where, for example, patents combining the development of the active component (C) with the manufacturing technology (B) are a common combination (BC). The table below shows how IPC classes refer to technology areas within hydrocracking.

Insert Table 1 about here

However, while the subclasses are generally related, as seen above, exceptions exist where a few specific IPC classes are mutually exclusive from the rest of the subclass. For instance, in the above table we exclude the IPC subclasses C10G-47/24-30 from C as these constitute a competing technology to hydrocracking, which utilizes an entirely different technology and cannot be compared to the hydrocracking process.

Our patent sample within hydrocracking consists of 3,902 patents from 1977 to 2007 collected from the Derwent Innovation Index. We identified 26 firms with five or more patents in this period from the assignees of these patents, for which we have collected firm level data. This yields a data set of 2,416 patents associated with these firms, with the remaining patents assigned to individuals, universities or firms with fewer than five hydrocracking patents. In order to obtain a measure of patent value, we linked our patent data to the OECD 2010 citations database (Webb, Dernis et al. 2005), which contains citation data for all WO and EPO patents. However, these data are not complete, as far from every patent is submitted to the WO or EPO. It is not uncommon that patents are submitted to a national patent office only, and not to the international patent offices. Patents not submitted to the WO and EPO are commonly patents of little or no commercial value or patents that are not important enough for the

[1] A combination of different technology areas is based on the nature of the innovation and the technologies utilized, not on the patent claim itself.

firm to have worldwide coverage. It is particularly firms in the US, Japan, and China that submit numerous patents to their national patent offices only. Therefore, when each patent family is counted only once, when only patents that are applied for by applicants with more than five patents in total are used, and when the patent families are linked to the OECD citations dataset, and the data is linked to the variables needed the result is a total of 934 patent families. The findings presented in this paper may therefore be biased towards firms with significant investments in the technology, in that they have five or more patents published by the WO/EPO.

Dependent variable

PAT_VAL

Our empirical study adopts a multidimensional conceptualization of patent value, inspired by Lanjouw and Schankerman (1999), that captures both technological importance and market value. Indeed, most of the measures available in the literature rely predominantly on either dimension (Gambardella, Harhoff et al. 2008; van Zeebroeck and van Pottelsberghe de la Potterie 2011). Our dependent variable (Pat_Val) combines two measures: standardized technological importance (expressed by forward citations) and standardized geographical scope (expressed by family size). Patent value is therefore defined as:

$$PAT\_VAL = \mathrm{st}(forward\ citations) + \mathrm{st}(family\ size)$$

Explanatory variables

1-RARITY OF INVENTION

We develop a measure as a proxy for the rarity of a patent in the industry that considers both the technology area it refers to, and the extent to which it results from a recombination of technological capabilities. With the help of an expert, we identified three broad technology areas that characterize the Hydrocracking technology: “process technology” (category A), “catalyst preparation” (category B), and “feeds and products” (category C). Table 1 shows the IPC codes defining each category. The IPC codes that describe a given patent may be associated to a single, a couple or all three technology categories. This allows us to propose a seven-fold classification of the technological areas of hydrocracking patents. We measure the non-rarity of a given patent as the ratio between the number of patents described by the same category as the focal patent registered up until the given year, and the total number of registered patents. Rarity is defined as one minus this ratio.

$$1 - RARITY\ OF\ INVENTION = 1 - \frac{\sum Patent\ type\ , t_n}{\sum Patents\ types\ in\ industry, t_n}$$

As we assume a curvilinear relationship between rarity and patent value, we include in our regression models also a squared term of this variable.

UNCERTAINTY OF ENVIRONMENT

We capture the uncertainty of the technological environment using the measure suggested by Luque (2002), and applied in a variety of studies, for example Park, Park and Lee (2012). This measure considers the annual variation rate of the patents generated in a given industry or relative to a given technology. In the formula:

$$\Delta P_{it-(t-1)=\frac{NPit-NPi(t-1)}{NPi+NPi(t-1)/2}}$$

the term $\Delta P_{it-(t-1)}$stands for the percentage change in industry *i* at time *t* and NP_{it} is the number of patents assigned to industry *i* at time *t*.

As we assume a curvilinear relationship between environmental uncertainty and patent value, we include in our regression models also a squared term of this variable.

LOW and HIGH UNCERTAINTY

The variables Low_Uncertainty and High_Uncertainty are generated as dummy variables, taking 1 when Uncertainty is respectively one standard deviation below and above mean.

Control variables

We apply both firm specific and patent specific controls. At the firm level, control variables are included for firm size, operationalized as the number of employees, and the level of firm internationalization, operationalized as the number of branch locations. We gathered these data from ORBIS. These are included as our data cover both large fully-integrated oil firms and smaller firms with a narrower focus. We control for industry experience, as a measure for the size of the R&D departments by including the total number of hydrocracking patents applied. The degree of *firm specialization* is defined as the degree to which a firm has more patents within a single technology area or a combination of technology areas than the majority of the firm population in a given year. The majority of the population is defined as 90% of the firms, meaning that a firm needs to have a higher share of patents within a specific technology or technology combination than 90% of the population to be identified as a specialized firm. As the threshold is identified by the type of patent, it reflects the relative prevalence of the type. This variable changes over time, with some firms starting out as highly specialized but losing this label as they accumulate patents in different technology areas. The reverse also occurs, when a firm starts out with a broad patent portfolio, but switches to developing primarily a single technology or technology combination above all else. We also control for prior specific experience accumulated in the specific patent type as share of the total accumulated number of hydro cracking patents in the firm in t-1.

At the patent level, a number of control variables are included: the age variable is a count variable indicating the number of years since the patent was applied for. To control for patents receiving input from external scientific sources such as universities, a dummy variable measuring whether the focal patent cites non-patent related literature is included. We also control for the number of inventors as well as the number of assignees to ensure that the both the number of persons and firms behind the invention is controlled for. Other measures prior identified as being indicators of patent value at patent level is whether the patent is granted, why a dummy variable taking 1 if granted is used, and whether the patent has been an opposed a dummy variable taking 1 if the patent has been opposed.

STATISTICAL METHOD & RESULTS

Method

In order to improve our understanding of the conditions under which capabilities are a source of competitive advantage and superior performance, we conducted a study aimed at assessing how the rarity of capabilities and the level of uncertainty affect the value of a technological invention. For this reason, the unit of analysis of our study is the individual invention, operationalized as a patent.

The empirical analyses are conducted in three stages: first, we explore the relationship between patent value and technological rarity, then we consider also the effect of environmental uncertainty; finally, we explore the moderating effect of a low or high uncertainty environment on the relation between technological rarity and patent value. The dependent variable of these models (Pat_Val) is censored, being the product of standardized forward citations and standardized family size, with values ranging between -1.989 and 15.115. Even though Tobit model is appropriate for censored data (Wooldridge 2009), given the presence of only four observations at the lowest value, we rely on OLS estimations. The model can be written in the following way:

$$Pr(PAT\_VAL) = r, r^2, u, u^2, r * u_{low/high}, r^2 * u_{low/high,}\ u_{low/high,} c$$

Where the probability of generating high value patents (PAT_VAL) depends on the ratio of rarity (r) and rarity squared (r^2), a ratio of uncertainty (u) and uncertainty squared (u^2), the dummy for low uncertainty (u_{low}), the dummy for high uncertainty u_{high}, and the control variables denoted c.

Descriptive statistics are presented in Table 2 and correlations in Table 3. In Table 2 it can be seen that the explanatory variable Rarity of inventions ranges from 0.03 to 1 and takes a mean of 0.465 with a standard deviation of 0.254, indicating that the data points are spread out over the range of possible outcomes. In Figure 1 the variance in hydrocracking patents over time was presented, showing peaks in 1984 and 1999. This descriptive graph indicates an environment that changed over time. The uncertainty variable also reflects this: in the range from -1.259 to 2 the mean is 0.150 with a standard deviation of 0.542 indicating high variance.

We present pairwise correlations in Table 3. It is interesting to notice the very low correlation (0.04) between the two patent value indicators Forward citations and Family size. This indicates that the two measures might, as expected, be expressions for different dimensions of value. We will perform a robustness analysis taking them individually into account, in order to verify the results from the measure we propose for patent value.

Insert Table 2 & 3 about here

4.2 Regression results

Table 4 shows our regression results. Model 1 is the baseline model including only the controls; in Model 2 and 3 examine separately the effects of Rarity and Uncertainty while Model 4 presents the fully specified model; finally, Model 5 and 6 consider the interaction between Rarity and, respectively, low and high Uncertainty.

We start our analysis addressing *Hypothesis 1* that the relationship between the value of an innovation and rarity is curvilinear and takes an U-shape. Model 4 shows that both the linear and the squared term of Rarity are significant, the former with negative sign and the latter with positive sign. This indicates a U-shaped relationship between the rarity and patent value, as graphically represented by Figure 2. This result is consistent with Model 2, considering the effect of Rarity alone.

These results provide support to the expectations of Hypothesis 1, indicating that highly valuable inventions are those building either on rare or non-rare technological capabilities.

Model 4 provides support also for *Hypothesis 2* stating that the relationship between the value of an innovation and environmental uncertainty is curvilinear and takes an inverted U-shape, as the graphical representation in Figure 3 shows. Both the linear and the squared term of Uncertainty are significant, with respectively a positive and a negative sign. We find partial support for this result in Model 3, in which the quadratic term is slightly beyond the 10% significant threshold.

This indicates that only a moderate level of technological dynamism is beneficial for the value of invention.

From these models we learn that the optimal environmental conditions for development of valuable inventions are a moderate uncertainty. Model 5 and 6 help our understanding of the drivers of value when uncertainty takes value outside this optimal area of uncertainty. While conditions of high uncertainty (Model 6) do not affect the relationship between rarity and patent value, we find statistical significant results for the moderating effect under low uncertainty (Model 5). Figure 4 shows graphically that the change in the relationship indicates a flattening of the curve, providing support to *Hypothesis 3b,* while *Hypothesis 3a* is not supported.

Insert Table 4, Figure 2, 3 and 4 about here

For what concerns the controls, the models consistently show that patents that rely on scientific knowledge, have multiple inventors and have been granted and opposed are associated with higher value.

ROBUSTNESS CHECKS

In order to validate the reliability of our findings, we apply a Tobit regression to the models we tested using an OLS regression. The use of a Tobit is indicated as our dependent variable is censored; however, it presents only four observations at the lower limit. The results are presented in Table 5 (not considering the interaction between high uncertainty and Rarity). We applied to these results the tests indicated by Wiersema and Bowen (2009) and Bowen (2012) [results not presented here], finding that they and are consistent with the results of our principal model.

Insert Table 5 about here

Furthermore to address the issue associated to the use of a compound dependent variable, we run all models with both Forward citations and Family size as dependent variable individually. In Table 6 we present the results from negative binomial regression models (Models 12-16), where the dependent variable is number of forward citations, finding that the key explanatory variables maintain sign and significance.

Insert Table 6 about here

In Table 7 (Model 17 to 21) we also run all specifications utilizing only the count of Family_Size as dependent variable. Interesting the results is significantly different when analyzing the moderating effect in Model 20. While all controls' results remain consistent with main results, the results for the interaction becomes insignificant, and the direction of the coefficients is opposite of the main results, and the results taking only Forward citations into account. This could indicate that be interpreted as during low uncertainty utilizing the family size measure as dependent variable is less reliable, as this indicator is a firm driven indicator.

Insert Table 7 about here

Also tests concerning different specifications of specialized firms were conducted. In our main models we use a measure indicating whether the firm behind the invention is specialized in terms of its patent portfolio in comparison to other industry players. The majority of the population is defined as 90% of the firms. In robustness checks we use two other specifications of specialization, considering a threshold at 75% and at the level of mean plus one standard deviation. Employing these specifications, the results remain unaffected.

Conclusive remarks

In this study, we theorized and examined a central research question: under what conditions do rare and non-rare capabilities contribute to superior innovation value? This paper investigates the relationship between rarity of a capability and competitive advantage. The notion that unique resources provide a competitive advantage is one of the core concepts of the Resource Based View that recently has been subject to critical assessment by a handful of studies (Kor and Leblebici 2005; Teece 2007; Newbert 2008; Drnevich and Kriauciunas 2011). We bring a contribution to this emerging stream of research by investigating the limits of rarity as a source of value for the firm.

The analysis of the effect of rarity of the capability an invention builds on its value found evidence of positive returns of generating less rare innovations beyond a certain point, identifying the positive returns from generating non-rare innovations. This indicates that both capabilities that are idiosyncratic to a firm and those that are widely diffused in an industry lead to superior performance. These results provides empirical support to the core theoretical proposition of the Resource Based View that rarity of resources and capabilities permit firms to develop a competitive advantage – in this case, an innovation-based strategy – that ultimately drives to a superior performance. This result is in line with the findings of Newbert (2008). Furthermore, they help our understanding of the *limits of rarity*. While Drnevich and Kriauciunas (2011) find that rarity of capaibilites relative to the development of the current activities of a firm does not deliver a superior value, we find that non-rarity of a capability can be a driver of competitive advantage.

This paper has also shown that that an optimum level of uncertainty permits firms to build a competitive advantage based on innovation strategy, in accordance with the insights offered by (Ragatz, Handfield et al. 2002; Bingham, Eisenhardt et al. 2007; Bingham and Haleblian 2012). Our data shows that conditions of both low and high uncertainty dampen the value of an invention, as they do not provide adequate incentives to innovate. We argue that a moderate level of uncertainty leaves room to experimentation and to the introduction inventions that could fit – or even trigger – the evolution of the technological trajectory. Instead, we argue that in conditions of low uncertainty tendency to develop incremental improvements of an existing technology reduces the value of inventions, as does the tendency to imitate competitors' strategy in conditions of high uncertainty. We believe that these results contribute to better specify the effect of uncertainty within the framework of the Resource Based View. These results are also relevant to the specialized stream of literature that investigates patent value (eg. Harhoff, Scherer et al. 2003; Gambardella, Harhoff et al. 2008), as they underscore the importance of including environmental factors in this analysis.

We suggest that these results are important for the development of studies in management of innovation, as they help disentangling the factors underlying the generation of valuable inventions. The findings reported in this paper shed further light on how innovation value is affected by both the level of rarity of competence of a firm and level of uncertainty of technology. Importantly, we show that even in the case of a mature technology, innovation can be the outcome of different strategic pattern, characterized, in this case, by the development of either rare or non-rare capabilities.

As all research, this study is not immune from limitations. First, our data permit us to observe only inventions that are patented: we are not able to observe the competences that have been deployed in projects that generated inventions that were not patented, such as those protected by trade secrets, or that proved to be unsuccessful and did not lead to a patent. Relatedly, we are not able to observe to what extent competences developed in failure projects have subsequently underpinned successful inventions. Future studies could pursue a closer investigation of how environmental uncertainty and existing competence endowment of a firm impact on the trial-and-error process of invention, and how capabilities are transferred to related inventions. Second, our study focuses on the single invention, rather than on the clusters of inventions that typically give rise to an innovation. In other words, we look at the value of single patents, without considering complementarities with existing or future inventions. Future research could examine the nature of capabilities needed to exploit these complementarities. Such studies could analyze a firm's product portfolios in combination with its patent portfolio. In this study, however, we addressed this effect by including for each firm the total number of patents within hydrocracking, and by measuring the firms' degree of specialization at each point in time. With regard to our empirical measures, it should be noticed that our classification of technological capabilities relies on IPC codes. These codes are attributed to patents by examiners of patent offices, and thus they are prone to some degree of subjectivity. Although use of such codes is standard in patent studies, we validated and improved the measure discussing their use with both technical experts and patent experts with years of experience specific to this industry. Finally, we restrict our analysis to a single technology employed in a single industry; this raises the question of the generalizability of our findings, thus further research could address other technologies that are applied in different industries.

Despites these limitations, we believe that this paper brings a worthwhile contribution to the academic debate on the resource based view and on management of innovation, and also offers important insights for firm management. Managers may be interested in our finding that non-rare capabilities – that arguably require lower investments and shorter time to be deployed compared to firm-specific capabilities – may contribute to the value of an invention as much as a rare capabilities. Managers should also consider the external forces that affect the development of a technological trajectory, and in particular environmental uncertainty. We find that predictability of the environment lowers the expected value of innovation, requiring managers to assess more carefully investments to develop rare capabilities.

TABLES AND FIGURES

Figure 1 – Patent applications annually within hydrocracking and accumulated hydrocracking patents

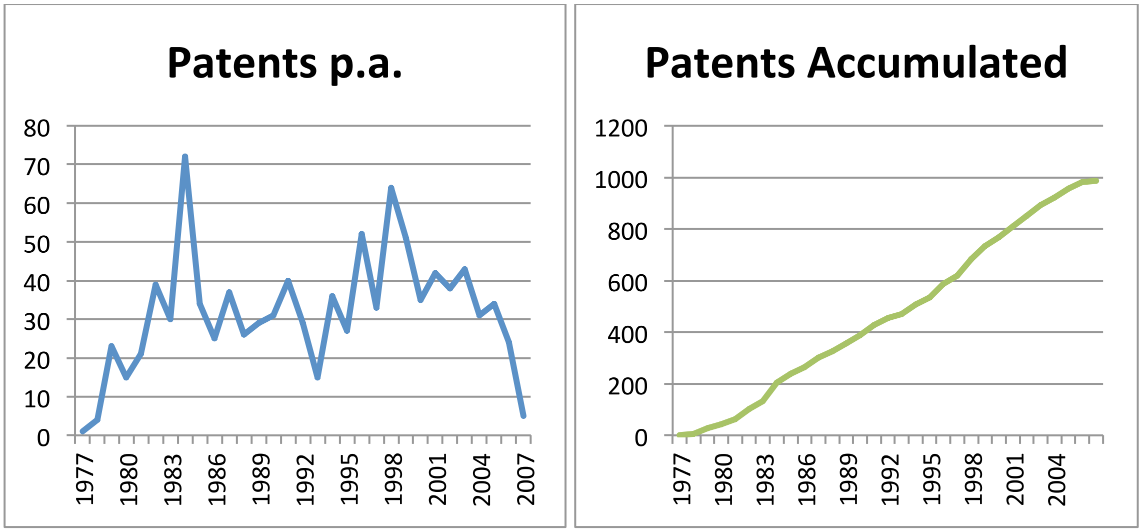

Figure 2: Graphical plot of U-shape relationship between 1-rarity and patent value

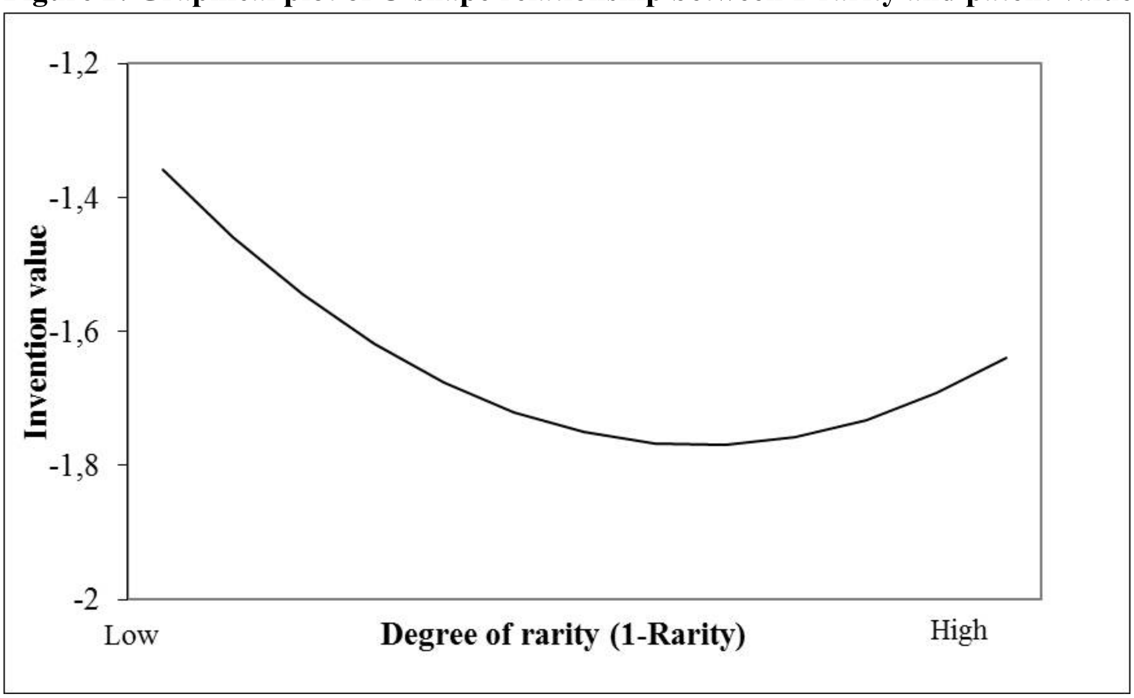

Figure 3: Graphical plot of Inverted U-shape relationship between uncertainty and patent value

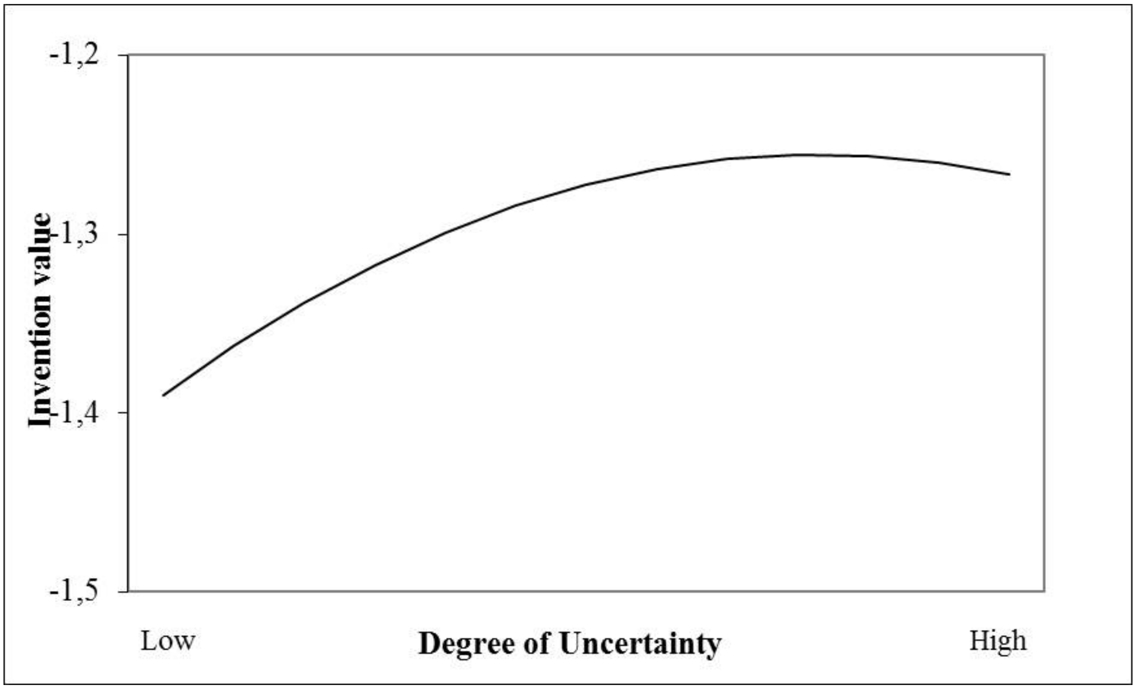

Figure 4: Graphical plot of inverted U-shape relationship between uncertainty and patent value, moderated by low uncertainty

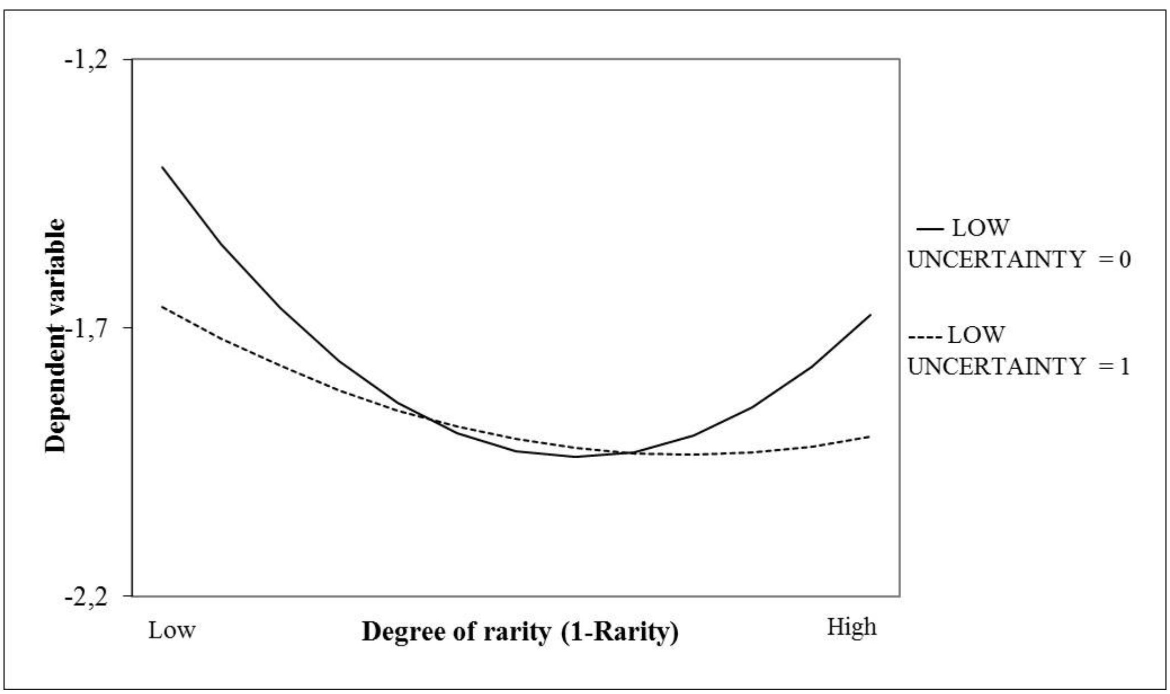

Table 1 Hydrocracking technology areas and IPC classes[2]

Technology area	Associated IPC classes	Excluded IPC classes	Percentage of observations
Process technologies (A)	C10G-065/00 B01J-008/00		5%
Catalyst preparation (B)	B01J-021/00 to B01J-049/00	B01J-023/76 B01J-029/00	21%
Feeds and products (C)	C10G-045/00 C10G-047/00 C10G-049/00	C10G-045/44 C10G-045/54 C10G-045/58 C10G-047/24-30	8%
AB AC BC ABC	Combinations of above classes		4% 13% 37% 11%

Table 2: Descriptive statistics

Variable	Mean	Std. Dev.	Min	Max
Patent value	.001	1.446	-1.988	151.154
Forward citations	3.124	6.155	0	95
Family size of patent	1.073	7.253	0	111
1-Rarity of invention	.465	.254	.029	1
1-Rarity of invention (sq)	.281	.238	.0008	1
Uncertainty of environment	.149	.541	-1.259	2
Uncertainty of environment (sq)	.315	.418	.0015	4
Low uncertainty (dummy)	.111	.314	0	1
Non patent related citations (dummy)	.085	.280	0	1
Specialized firm	.200	.400	0	1
Experience	.546	.838	-16	1
Internationalization	1.435	1.814	0	6.302
Firm size	8.004	368.987	0	1.171
Patents age	1.380	7.774	0	29
Experience within the industry	6.620	6.511	1	246
Patent grant	.602	.489	0	1
Patent opposition	.009	.097	0	1
Number of inventors on patent	4.585	4.326	1	74
Number of assignees on patent	1.841	.954	1	10

[2] IPC classes ending in /00 signify that all nine-digit subclasses within the seven-digit class are included, unless otherwise noted.

Table 3: Correlation matrix

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	Patent value	1.00																		
2	Forward citations	0.72	1.00																	
3	Family size of patent	0.72	0.04	1.00																
4	1-Rarity of invention	-0.02	0.09	-0.11	1.00															
5	1-Rarity of invention (sq)	-0.00	0.11	-0.11	0.97	1.00														
6	Uncertainty of environment	0.08	0.12	-0.01	0.08	0.10	1.00													
7	Uncertainty of environment (sq)	0.01	0.13	-0.11	0.15	0.18	0.56	1.00												
8	Low uncertainty (dummy)	-0.03	-0.01	-0.04	0.01	0.02	-0.51	0.10	1.00											
9	Non patent related citations (dummy)	0.09	0.04	0.10	0.11	0.09	-0.12	-0.04	0.03	1.000										
10	Specialized firm	0.01	0.03	-0.01	0.00	-0.00	-0.03	-0.03	-0.05	-0.07	1.00									
11	Experience	-0.03	-0.10	0.05	-0.37	-0.40	-0.09	-0.32	-0.02	-0.07	-0.01	1.00								
12	Internationalization	0.02	0.04	-0.01	0.08	0.08	-0.04	-0.06	-0.03	0.04	0.16	-0.05	1.00							
13	Firm size	0.06	0.00	0.08	0.01	0.02	-0.01	-0.01	-0.05	0.07	-0.25	-0.10	0.28	1.00						
14	Patents age	0.12	0.31	-0.14	0.25	0.29	0.33	0.48	0.08	-0.05	-0.08	-0.21	0.05	0.04	1.00					
15	Experience within the industry	-0.08	-0.17	0.05	-0.22	-0.22	-0.09	-0.18	-0.02	-0.03	-0.24	0.17	-0.36	0.01	-0.47	1.00				
16	Patent grant	0.32	0.18	0.28	0.03	0.03	0.18	0.17	0.04	0.03	0.03	-0.05	-0.04	-0.10	0.42	-0.25	1.00			
17	Patent opposition	0.10	0.01	0.13	-0.01	-0.02	-0.01	-0.03	-0.03	0.01	0.03	0.00	0.02	-0.04	-0.04	0.03	0.08	1.00		
18	Number of inventors on patent	0.33	-0.00	0.48	-0.04	-0.06	-0.10	-0.16	-0.03	0.09	0.01	0.05	-0.08	0.00	-0.31	0.21	-0.02	0.04	1.00	
19	Number of assignees on patent	0.15	-0.06	0.27	-0.02	-0.04	-0.10	-0.19	-0.05	0.14	0.02	0.06	-0.05	0.17	-0.34	0.07	-0.04	0.05	0.30	1.00

Table 4 OLS regression, dependent variable is patent value

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
1-Rarity of invention		-1.983***		-2.026***	-2.353***	-2.128***
		[0.291]		[0.293]	[0.321]	[0.711]
1-Rarity of invention (sq)		1.778***		1.799***	2.175***	1.901**
		[0.379]		[0.380]	[0.390]	[0.760]
Uncertainty of environment			0.186**	0.194**		
			[0.071]	[0.075]		
Uncertainty of environment (sq)			-0.231	-0.261*		
			[0.144]	[0.132]		
1-Rarity of invention* Low uncertainty (dummy)					2.868**	
					[1.114]	
1-Rarity of invention (sq)* Low uncertainty (dummy)					-3.035***	
					[0.980]	
Low uncertainty (dummy)					-0.641**	
					[0.245]	
1-Rarity of invention* High uncertainty (dummy)						0.640
						[2.189]
1-Rarity of invention (sq)* High uncertainty (dummy)						-0.587
						[1.921]
High uncertainty (dummy)						0.051
						[0.551]
Non patent related citations (dummy)	0.229	0.284*	0.257	0.315*	0.302*	0.294*
	[0.160]	[0.164]	[0.164]	[0.168]	[0.168]	[0.168]
Specialized firm	0.063	0.056	0.066	0.059	0.050	0.043
	[0.104]	[0.105]	[0.102]	[0.104]	[0.105]	[0.111]
Experience	-0.003	-0.022	-0.027	-0.052	-0.021	-0.028
	[0.083]	[0.082]	[0.081]	[0.079]	[0.082]	[0.085]
Internationalization	0.028	0.028	0.025	0.025	0.027	0.031
	[0.043]	[0.043]	[0.041]	[0.041]	[0.043]	[0.042]
Firm Size	0.022	0.020	0.022	0.019	0.018	0.019
	[0.014]	[0.014]	[0.014]	[0.015]	[0.015]	[0.015]
Patent Age	0.026***	0.026***	0.027**	0.027**	0.026***	0.020**
	[0.009]	[0.009]	[0.010]	[0.010]	[0.009]	[0.008]
Experience within the industry	-0.000	-0.001	-0.000	-0.001	-0.000	-0.001
	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]
Patent grant	0.794***	0.782***	0.778***	0.763***	0.789***	0.784***
	[0.066]	[0.065]	[0.069]	[0.068]	[0.064]	[0.061]
Patent opposition	0.895	0.939*	0.895*	0.939*	0.926*	0.941*
	[0.530]	[0.528]	[0.527]	[0.524]	[0.537]	[0.530]
Number of inventors on patent	0.117***	0.118***	0.117***	0.118***	0.118***	0.118***
	[0.028]	[0.029]	[0.028]	[0.029]	[0.029]	[0.030]
Number of Assignees on patent	0.128**	0.135**	0.122**	0.130**	0.135**	0.132**
	[0.061]	[0.061]	[0.059]	[0.059]	[0.059]	[0.061]
Constant	-1.840***	-1.381***	-1.772***	-1.293***	-1.305***	-1.292***
	[0.211]	[0.223]	[0.218]	[0.230]	[0.226]	[0.219]
R-squared	0.244	0.253	0.248	0.257	0.256	0.255
Adj.R-squared	.2347247	.2422059	.2368784	.2449886	.2427993	.2418396
No of Obs	934	934	934	934	934	934
F test	67.77946***	156.9885***	61.59315***	153.5754***	137.2706***	169.3541***

* p<0.1, ** p<0.05, *** p<0.01

Table 5 Tobit regression, dependent variable is patent value

	Model 7	Model 8	Model 9	Model 10	Model 11
1-Rarity of invention		-1.996***		-2.053***	-2.350***
		[0.270]		[0.264]	[0.310]
1-Rarity of invention (sq)		1.795***		1.825***	2.166***
		[0.314]		[0.316]	[0.347]
Uncertainty of environment			0.213***	0.223***	
			[0.075]	[0.078]	
Uncertainty of environment (sq)			-0.282*	-0.314**	
			[0.146]	[0.130]	
1-Rarity of invention*Low uncertainty (dummy)					2.721**
					[1.061]
1-Rarity of invention (sq)*Low uncertainty (dummy)					-2.822***
					[0.969]
Low uncertainty (dummy)					-0.654***
					[0.252]
Non patent related citations (dummy)	0.229	0.285*	0.262	0.321*	0.303*
	[0.163]	[0.164]	[0.164]	[0.165]	[0.167]
Specialized firm	0.063	0.055	0.067	0.060	0.050
	[0.093]	[0.098]	[0.092]	[0.099]	[0.099]
Experience	-0.004	-0.022	-0.033	-0.058	-0.022
	[0.061]	[0.062]	[0.054]	[0.054]	[0.062]
Internationalization	0.029	0.029	0.025	0.025	0.028
	[0.026]	[0.026]	[0.026]	[0.025]	[0.026]
Firm size	0.021	0.019	0.021	0.018	0.017
	[0.014]	[0.014]	[0.014]	[0.014]	[0.014]
Patents age	0.026***	0.026***	0.028***	0.029***	0.027***
	[0.007]	[0.007]	[0.008]	[0.008]	[0.007]
Experience within the industry	-0.000	-0.001	-0.000	-0.001	-0.000
	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]
Patent grant	0.794***	0.782***	0.775***	0.760***	0.788***
	[0.063]	[0.061]	[0.065]	[0.062]	[0.059]
Patent opposition	0.894	0.939*	0.895*	0.939*	0.923*
	[0.543]	[0.539]	[0.539]	[0.534]	[0.546]
Number of inventors on patent	0.117***	0.118***	0.117***	0.118***	0.118***
	[0.023]	[0.024]	[0.023]	[0.023]	[0.024]
Number of assignees on patent	0.132**	0.139**	0.126**	0.133**	0.139**
	[0.063]	[0.062]	[0.061]	[0.060]	[0.061]
Constant	-1.852***	-1.391***	-1.774***	-1.289***	-1.314***
	[0.139]	[0.148]	[0.153]	[0.161]	[0.154]
sigma Constant	1.262***	1.255***	1.258***	1.251***	1.252***
	[0.011]	[0.011]	[0.010]	[0.010]	[0.011]
No of Obs	934	934	934	934	934
Uncensored o~s	930	930	930	930	930
Log likelyhood	-1.543.876	-1538.26	-1.540.763	-1.534.642	-1536.28
Pseudo R-squ~d	.0782187	.0815721	.0800777	.0837321	.0827542
F test	439.7257***	399.1957***	362.471***	279.8561***	460.9796***

* p<0.1, ** p<0.05, *** p<0.01

Table 6 Negative Binomial regression, dependent variable is Forward Citations

	Model 12	Model 13	Model 14	Model 15	Model 16
1-Rarity of invention		-2.058***		-2.017***	-2.744***
		[0.334]		[0.331]	[0.357]
1-Rarity of invention (sq)		2.029***		1.913***	2.825***
		[0.408]		[0.414]	[0.430]
Uncertainty of environment			0.198**	0.201**	
			[0.101]	[0.099]	
Uncertainty of environment (sq)			-0.408***	-0.418***	
			[0.131]	[0.126]	
1-Rarity of invention*Low uncertainty (dummy)					5.603***
					[1.967]
1-Rarity of invention (sq)*Low uncertainty (dummy)					-6.596***
					[1.979]
Low uncertainty (dummy)					-0.835**
					[0.416]
Constant	-0.582*	-0.124	-0.531*	-0.061	-0.036
	[0.315]	[0.334]	[0.309]	[0.326]	[0.322]
lnalpha					
Constant	0.132**	0.111	0.120*	0.098	0.092
	[0.067]	[0.070]	[0.070]	[0.074]	[0.070]
Pseudo LL	-1.962.886	-1.957.758	-1.958.934	-1.953.643	-1.952.594
No of Obs	934	934	934	934	934
Wald-Chi2	642.6914***	1336.384***	793.2447***	1913.349***	2094.292***

* p<0.1, ** p<0.05, *** p<0.01

Table 7 Negative Binomial regression, dependent variable is Family Size

	Model 17	Model 18	Model 19	Model 20	Model 21
1-Rarity of invention		-0.551***		-0.574***	-0.501***
		[0.168]		[0.168]	[0.181]
1-Rarity of invention (sq)		0.308*		0.322*	0.224
		[0.162]		[0.166]	[0.172]
Uncertainty of environment			0.083**	0.089***	
			[0.035]	[0.031]	
Uncertainty of environment (sq)			-0.106*	-0.124**	
			[0.059]	[0.058]	
1-Rarity of invention*Low uncertainty (dummy)					-0.425
					[0.464]
1-Rarity of invention (sq)*Low uncertainty (dummy)					0.688
					[0.471]
Low uncertainty (dummy)					-0.033
					[0.471]
Constant	1.798***	1.972***	1.826***	2.011***	1.971***
	[0.087]	[0.092]	[0.084]	[0.087]	[0.089]
lnalpha					
Constant	-2.334***	-2.371***	-2.348***	-2.387***	-2.376***
	[0.353]	[0.361]	[0.353]	[0.361]	[0.361]
Pseudo LL	-2.672.592	-2.662.187	-2.669.193	-2.657.988	-2.660.929
No of Obs	934	934	934	934	934
Wald-Chi2	2122.063***	3003.254***	2369.501***	2908.646***	3645.035***

* p<0.1, ** p<0.05, *** p<0.01

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