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The Innovative Performance of R&D Outsourcing[1]

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Abstract. Firms increasingly outsource their R&D activities to external actors, but little is known about how this R&D strategy relates to the value of their research output (in terms of invention quantity as well as quality). To study this issue, I analyse a pooled cross-sectional dataset of German manufacturing firms. The results obtained from the data analysis suggest that R&D outsourcing as well as the interaction between this strategy and internal R&D are significantly and positively associated with invention quantity but not with invention quality. Furthermore, the estimation results show that manufacturing rather than service companies are more likely to explore both internal and external R&D strategies to generate inventions. Besides that, the data analysis indicates that R&D outsourcing is more important innovative input for firms operating in science-based industries than in scale-intensive and specialized-supplier sectors.

Keywords. R&D Outsourcing, Internal R&D, Patent, Invention Quantity, Invention Quality, Pavitt's Sectoral Taxonomy.

1 Introduction

Nowadays, firms are under great pressure to reduce the costs of their R&D activities and to speed up their new technology and product development to respond efficiently and effectively to the increased global competition, the fast pace of technological changes and shortened product life cycles (Chesbrough, 2003; Chesbrough et al., 2006; Holcomb & Hitt, 2007; Keupp & Gassmann, 2009). All these requirements lead firms to open up their R&D boundaries to access required external resources timely. Drawing on the R&D management literature, scholars differentiate two generic strategies for sourcing external knowledge via formal contracts: i) outsourcing R&D functions and ii) developing innovation jointly (Narula, 2001; Nakamura & Odagiri, 2005; Grimpe & Kaiser, 2010); the external actors are then R&D suppliers and innovation cooperation partners, respectively. The former strategy implies the acquisition of a research outcome from external actors, whereas the latter strategy refers to a joint effort of the partner firms to

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develop valuable knowledge assets. The main advantage attributed to R&D outsourcing[2] or external R&D is that this strategy allows firms to purchase ready R&D results without substantial involvement in the innovation activities, which are contracted out to external actors (Grimpe & Kaiser, 2010). In this context, R&D outsourcing permits firms to concentrate on core R&D activities internally and to outsource rather peripheral R&D tasks to specialized external suppliers (Quinn, 1999, 2000; Grimpe & Kaiser, 2010). As a consequence, R&D outsourcing may allow firms to acquire high-quality knowledge inputs from specialized suppliers and to share the costs and risks of R&D projects with them (Mowery, 1983; Dess et al., 1995; Gilley & Rasheed, 2000). Furthermore, by distributing R&D tasks among different external actors, firms shift their R&D activities from serial to synchronous actions so that these activities are implemented independently and simultaneously, resulting in an increased speed of R&D processes (Howells et al., 2003; Langlois, 2003; Ebrahim et al., 2009).

Although R&D outsourcing promises the above-mentioned advantages, this governance mode also has its drawbacks. First, distributing R&D activities among external providers may induce a firm to specialize in combining externally available technologies rather than to develop its own (West et al., 2006). In this context, outsourcer firms may shift their knowledge creation capabilities to specialized external suppliers (Bettis et al., 1992; Gilley & Rasheed, 2000; West et al., 2006). As a result, R&D outsourcing may deplete firms' research competencies and deteriorate their R&D performance (Bettis et al., 1992). The second issue is that the knowledge-based resources acquired from external actors via contracts may not be unique, because competitors may have access to the expertise of the same supplier (Grimpe & Kaiser, 2010). In other words, knowledge may unintentionally spillover from a supplier to multiple clients firms while working with them. Moreover, R&D outsourcing may replace learning-by-doing activities in internal R&D and, hence, deteriorate a client firm's integrative competencies. Consequently, this strategy may hamper the overall innovative performance of the firm (Bettis et al., 1992; Weigelt, 2009). Given these mixed potential value-creating outcomes of R&D outsourcing, the question arises of whether those firms that outsource R&D tasks generate a higher-quality research output from their R&D processes than their counterparts that do not invest in this strategy.

Motivated by this question, a number of studies examine the relationship between R&D outsourcing and R&D output, in which the quality of the R&D output is most commonly measured as sales from product innovations (Grimpe & Kaiser, 2010) and patent counts (Beneito, 2006). These papers contribute significantly to our understanding of the performance implication of R&D outsourcing, but the indicators of R&D output (e.g. sales from product innovation, patent counts) used in the studies may not reflect the overall quality of outsourcer firms' research processes. For example, a product innovation might be a result of combining externally available knowledge inputs, and it may not be a good indicator of the quality of the internal research process. In other words, the knowledge and production boundaries of a firm may differ (Brusoni et al., 2001). An

[2] The terms R&D outsourcing and external R&D are used interchangeably in this study.

alternative measure of R&D output, such as patent counts, shows firms' property rights upon their inventions, but patents may vary significantly in terms of their quality and innovative contents (Griliches, 1990). Therefore, further research is required to understand how R&D outsourcing is associated with the quality of a firm's research output. Besides that, little is known about how firms operating in different industries explore internal and external resources to generate high quality inventions. The importance of internal and external R&D strategies may depend on the features of industries' technological regimes and trajectories, market structure and appropriability conditions. Based on these characteristics, Pavitt (1984) differentiates four major sectoral patterns of innovative activities such as supplier-dominated, scale-intensive, specialized-supplier and science-based industries. Supplier-dominated firms are least innovative and mainly oriented towards process innovations. In contrast, remaining three sectoral classes belong to medium- and high-technology industries and they may explore both internal and external knowledge sources to innovate. Hence, further research is required to understand whether all firms benefit from combining internal and external knowledge sources or it depends on sector-specific characteristics of innovation activities (Cantner & Savin, 2014).

The empirical analysis is based on the data obtained from Mannheim Innovation Panel (MIP) and the European Patent Office (EPO). The former provides detailed information about the innovation activities of German firms (e.g. expenditures on internal and external R&D, product and process innovations, R&D cooperation partners, etc.), whereas the latter provides data about the patents applied for by German firms at the EPO. To measure the quality of a firm's R&D output, I use the average forward citations that the firm's patents obtain in subsequent seven-year windows after the filing year weighted by its patent counts. Besides that, I take patent counts as a dependent variable in the econometric analysis to measure firms' invention quantity.

Considering the total sample (manufacturing and services sectors together), the data analysis shows that R&D outsourcing is significantly and positively associated with invention quantity. As inter- rather than intra-firm knowledge-based resources are more likely to vary, those companies acquiring R&D from an external provider may have more chance of accessing diverse knowledge inputs and, as a result, performing better in invention activities than their counterparts that experiment only with internal knowledge. In other words, this strategy may help firms to access complementary knowledge inputs and, in this way, to improve their invention performance. However, the positive performance implication of R&D outsourcing does not appear to hold for invention quality. Similarly, the joint implementation of R&D outsourcing and internal R&D is only significant and positive for invention quantity but not for invention quality. Moreover, the estimation results suggest that firms operating in the manufacturing sector are more likely to use both internal and external knowledge sources (e.g. internal R&D, R&D outsourcing) to generate inventions than companies coming from the service sector. Besides that, the data analysis indicates that R&D outsourcing is the most important innovative input for firms operating in science-based industries than in scale-intensive and specialized-supplier sectors.

The rest of this chapter is organized in the following way. Section 2 discusses the theoretical arguments for the hypotheses development. Section 3 reviews the database and variables used in the econometric analysis. Section 4 presents the econometric methods. After that, Section 5 provides the estimation results and Section 6 concludes.

2 Literature review and hypotheses development

In this section, the relationship between R&D outsourcing and the inventive performance of a firm is examined. R&D outsourcing may allow firms to accelerate and improve their innovation activities and to respond swiftly to new market threats and opportunities (Quinn, 1999, 2000; Gilley & Rasheed, 2000; Howells et al., 2003; Calantone & Stanko, 2007; Howells et al., 2008). However, this strategy may also involve considerable risks in terms of declining internal R&D activities, depleting firms' research or knowledge-creation competencies and, as a result, deteriorating the overall performance of their R&D processes (Bettis et al., 1992; Weigelt, 2009). Therefore, the conditions under which it might be advantages to organize R&D activities internally or externally require careful consideration. In this context, insights from transaction cost theory (TCT) and the resource-based view (RBV) of the firm can be helpful. These two theories attempt to explain the boundaries of the firm, but from different perspectives. While TCT is considered to be a cost-based approach, the RBV of the firm is seen as a resource-oriented framework.

2.1 Transaction cost theory

TCT considers internal and external governance modes based on their relative costs; when the market offers a certain good or service at a lower price than organizing the same activities internally then a buy strategy is considered to be optimal (Coase, 1937; Williamson, 1975). TCT assumes that 'transactions within integrated companies may be insulated from competitive pressure and subject to bureaucratic phenomena' (Geyskens et al., 2006: 520). In this context, the market mechanism might be superior to the internal organization form, because the market competition forces suppliers to improve their efficiency and to lower their prices. However, the transaction or coordination costs might increase when firms use the market mechanism instead of the internal governance mode, because monitoring and enforcing a contract performance is often problematic due to bounded rationality, opportunism and asset specificity (Williamson, 1975). According to Simon (1955), humans have limited cognitive ability in spite of the assumption of their rationality. Hence, limited cognitive ability prevents firm managers from foreseeing all the possible opportunistic actions of their contractors. Opportunism is defined as the disregard of the contract partners or the defeat strategy that may also reduce the total welfare. To avoid such situations, firm managers attempt to write a complete contract; this, however, is only accomplishable when the contracted quantity and quality of specific assets are readily observable and measurable, which certainly is not the case with the outcome of product and process innovation activities. Usually, those activities are characterized by high levels of uncertainty with regard to outcomes (Mudambi & Tallman, 2010). Related to that, it is difficult to estimate the period of time and the resources required fulfilling certain research and development tasks. Hence, contracting those activities out will lead to high transaction costs (for monitoring the processes and results). To avoid excessive transaction costs, internal, rather than external, organizational forms for innovation activities appear to be more appropriate.

However, the transaction costs related to the market mechanism will be substantially lowered if a firm manages to modularize its innovation activities. Modularity implies that a complex engineering system is decomposed into discrete components, which are developed separately and then interconnected with a standardized interface to assemble the final product (Mikkola, 2003). This makes the inter-organizational division of labour possible at very low transaction costs through minimizing the interdependence between sub-components or modules (Mikkola, 2003). Hence, the modularization of product development functions enables firms to acquire some parts of R&D activities in the open marketplace. However, TCT alone does not explain why firms organize certain R&D activities internally and certain ones externally. As TCT is considered to be a cost-based approach, it neglects the learning processes embodied within internal and external governance modes. In other words, TCT focuses on minimizing transaction costs when considering which activities should be retained internally and which should be contracted out, but it ignores the ideas and technologies available inside and outside the firm (Barney, 1999). Therefore, to provide a complete picture of how firms set R&D boundaries, I present insights from the RBV of the firm in the next section.

2.2 The resource-based view of the firm

The RBV of the firm further discusses the resource allocation issue and shifts the attention from a cost-based approach towards a resource-oriented framework (Penrose, 1959; Barney, 1991; Peteraf, 1993; Barney et al., 2001). In particular, the RBV of the firm suggests understanding the performance of a firm via its combination of specific resources. Resources can be tangible and intangible assets, such as physical assets, financial capital, human capital, organizational knowledge, information, managerial capabilities, etc. (Grant, 1991). According to the RBV, firms should possess valuable, rare, inimitable and non-substitutable (VRIN) resources to attain above-normal profits (Barney, 1991; Peteraf, 1993). Valuable and rare resources enable firms to satisfy consumer requirements better than their competitors (Peteraf, 1993). Resources should also be inimitable and non-substitutable, because competitors should not be able to duplicate the valuable resources of the firm or to attain a comparable performance based on other resources. To develop VRIN resources, firms should define their organizational strengths and weaknesses relative to their rivals so that they can focus on the economic activities that they can perform best (Barney, 1991). As the internal governance mode is also considered to be one of the most powerful isolating mechanisms, organizing strategically important economic activities internally enables firms not only to build up valuable and rare resources but also to protect these resources from imitation (Wang et al., 2009; Grimpe & Kaiser, 2010). This is especially true in the case of R&D activities because protecting strategically important knowledge-based resources from imitation can be difficult once they have been revealed or contracted out to external actors (Grimpe & Kaiser, 2010). The knowledge-based view (KBV) of the firm, which is largely influenced by the RBV, considers knowledge as the most important resource of a firm (Grant, 1996). It suggests that tacit knowledge is relatively immobile and difficult to imitate and, therefore, it constitutes the basis for a superior performance. For this reason, firms should organize strategically important R&D functions internally and use the market mechanism for rather peripheral or non-core activities (Prahalad & Hamel, 1990; Grimpe & Kaiser, 2010). Inter-firm division of R&D labour has become more relevant in the current fast-changing market environment, because rapid technological changes and a shorter product life cycle deplete firms' valuable resources and put pressure on them to pursue innovation (Chesbrough, 2003).

As technological and product innovation also spans different scientific disciplines, many firms face a cognitive limitation in carrying out all the R&D tasks internally (Keupp & Gassmann, 2009). The internal impediments to innovation are more critical under rapid technological changes, because undertaking radical transformation and developing new competitive capabilities internally, in the short run, can hardly be achieved without external collaboration (Powell et al., 1996; Chesbrough, 2003; Keupp & Gassmann, 2009). Therefore, firms outsource some R&D activities to external specialized suppliers to gain timely access to required resources that are otherwise unavailable (Powell et al., 1996). In this context, R&D outsourcing may serve a complementary purpose and improve firms' invention performance.

2.3 R&D outsourcing and invention quantity

Several potential benefits can be realized as a result of R&D outsourcing. First, the division of R&D tasks among firms enables them to shift their R&D activities from serial to parallel working processes and, hence, to accelerate new product and technology development (Howells et al., 2003; Ebrahim et al., 2009). Second, by the division of R&D labour, firms increase the organizational commitment to the R&D activities that they can perform best and use the R&D service of specialized research organizations for rather peripheral innovation activities in which they lack competency (Quinn, 1999, 2000; Grimpe & Kaiser, 2010). In other words, inter-firm division of R&D labour enables companies to devote their financial and human resources to their core research activities and to acquire rather peripheral R&D functions from a specialized research organization to which these are the key activities (Prahalad & Hamel, 1990; Grimpe & Kaiser, 2010; Mudambi & Tallman, 2010). Accordingly, the specialized R&D organization may possess superior knowledge-based resources as well as a more appropriate research infrastructure and, therefore, it may carry out these R&D tasks better than they can be implemented by the client firm (Quinn, 1992; Gilley & Rasheed, 2000). As a result, R&D outsourcing may help firms to improve the efficiency and effectiveness of their R&D activities. In fact, prior research provides empirical evidence that the external R&D strategy is the important source of technology and product innovations (Cassiman & Veugelers, 2006; Beneito, 2006; Grimpe & Kaiser, 2010). Based on these arguments, a positive relationship between R&D outsourcing and invention quantity can be expected. Hence, the following hypothesis is proposed:

H1a: R&D outsourcing is positively associated with invention quantity.

2.4 R&D outsourcing and invention quality

Considering the composition of knowledge resources, the KBV of the firm suggests that a complementary rather than a substitutive relationship is more likely to result in superior performance (Nelson & Winter, 1982; Rosenkopf & Nerkar, 2001). Complementary resources allow firms to reconfigure their competencies by generating new combinations of existing resources to respond timely and effectively to new market opportunities and external threats. Moreover, given that an innovation is considered to be a new combination of the existing knowledge (Schumpeter, 1934), a firm that possesses a heterogeneous stock of knowledge and competencies has more opportunities for knowledge recombination and performs better in innovation than others that apply a rather homogeneous knowledge base (Nelson & Winter, 1982; Rosenkopf & Nerkar, 2001; Cantner & Plotnikova, 2009). Taking into account that firms are heterogeneous in terms of their resources due to their different routines and operation systems, which cause the formation and accumulation of diverse capabilities and competencies (Nelson & Winter, 1982), R&D outsourcing can help firms to access miscellaneous knowledge inputs and, as a result, to improve the quality of their R&D activities. Although knowledge-based resources sourced from R&D suppliers may not be unique and they might also be accessible by competitors, these external resources may enable firms to pursue a unique combination of external and internal knowledge, resulting in firm-specific resources (Grimp & Kaiser, 2010). Hence, the following hypothesis is proposed:

H1b: R&D outsourcing is positively associated with invention quality.

2.5 The inter-relationships between internal R&D, R&D outsourcing and invention performance

Although the R&D outsourcing strategy involves a number of advantages, this governance mode also has its drawbacks. First, a client firms may not be able to internalize the tacit knowledge component of outsourced R&D activities via arm's length transactions, because transferring such knowledge across organizational boundaries requires intensive interaction between transaction partners, which is not implied in this R&D strategy. Accordingly, R&D outsourcing may hollow out tacit knowledge applications in internal R&D and limit the firm's insights into codified knowledge components of innovation activities (Weigelt, 2009). Third, R&D outsourcing may reduce the internal learning-by-doing and problem-solving activities (Bettis et al., 1992; Weigelt, 2009; Grimpe & Kaiser, 2010), which are considered to be the primary source of new skills and know-how. In this sense, this R&D strategy may deplete a firm's research capabilities and shift knowledge creation competencies from the firm to an R&D supplier (Bettis et al., 1992). To mitigate the negative side of R&D outsourcing, firms should invest internal R&D to enhance internal learning-by-doing activities and to develop absorptive capacity. Absorptive capacity refers to 'the ability of a firm to recognize the value of new, external information, assimilate it, and apply it to commercial ends' (Cohen & Levinthal, 1990: 128). In particular, it stands for the pre-existing knowledge stock that allows a firm to identify and exploit external knowledge. As Cohen & Levinthal (1990) suggest, prior knowledge structure within a firm determines its ability to learn and add new knowledge to its memory. In this sense, companies with a rich internal knowledge stock are more likely to gain from R&D outsourcing in terms of utilizing knowledge effectively from an external supplier than their counterparts that lack the required level of competencies. In other words, a firm is more likely to learn and acquire new knowledge in a particular area of the technological domain in which it has already accumulated some level of expertise. In contrast, learning in new and unfamiliar technological areas can be limited due to the lack of associated linkages between the firm's knowledge basis and the new technological domain. Therefore, firms that invest in internal R&D are more likely to build up required level of absorptive capacity and to utilizing knowledge from R&D suppliers more effectively than their counterparts with lack of internal competencies. In fact, prior studies find that the marginal returns of external R&D increase if a firm simultaneously invest in internal R&D (Cassiman & Veugelers, 2006; Beneito, 2006; Grimpe & Kaiser, 2010). In this context, I assume that the joint implementation of internal R&D and R&D outsourcing is positively associated with invention performance. Thus, the following hypotheses are proposed:

> *H2a: The joint implementation of internal R&D and R&D outsourcing is positively associated with invention quantity.*
>
> *H2b: The joint implementation of internal R&D and R&D outsourcing is positively associated with invention quality.*

2.6 Pavitt's sectoral classes

The way in which firms organize their R&D activities may depend also on sector-specific characteristics of innovation activities. Given that 'sectoral patterns of technological innovation are different, one may expect that firms in specific sectors use specific internal and external resources in order to innovate successfully' (Oerlemans et al., 1998: 302). In this context, the importance of investing in both internal and external R&D activities may depend on the nature of technological regimes and trajectories in specific industries. In particular, Pavitt (1984) suggests that the pace and rate of technological change in any industry depends on the source of technology, the degree of technological cumulativeness, market structure and the appropriability conditions. Based on these characteristics, he identifies four main categories of manufacturing industries such as supplier-dominated, scale-intensive, specialized-suppliers, and science-based sectors. To extend the taxonomy to the service sector, Castellacci (2008) and Bogliacino & Pianta (2009) re-examine Pavitt's sectoral classes and propose a unified or revised version of the taxonomy covering both manufacturing and service industries. This revised version of Pavitt's taxonomy can be described as follows[3]:

(1) Supplier-dominated sectors contain industries that provide final goods and services (Cantner & Savin, 2014). In these sectors, firms lack in-house capabilities and expertise to organize innovation activities internally and, hence, they acquire machinery and equipment from external suppliers (Castellacci, 2008; Bogliacino & Pianta, 2009). Innovation processes in this sectoral class are also relatively low technological content and mainly oriented towards cutting costs (Pavitt, 1984; Castellacci, 2008; Bogliacino & Pianta, 2009; Cantner & Savin, 2014).
(2) Scale-intensive sectors are composed of industries that produce simple materials and consumer durables (i.e. the automotive sector) as well as sectors that offer financial services (i.e. financial intermediation, pension funding, etc.). In these industries, firms are generally large and exploit economies of scale. They may rely on both internal and external knowledge sources to develop product and process innovations. In scale-intensive industries, innovation activities are mainly oriented towards improving efficiency of production process (Castellacci, 2008; Bogliacino & Pianta, 2009).
(3) Specialised-supplier sectors include industries that produce advanced equipments and machinery components to be sold into other sectors. Firms in specialised-supplier industries are generally small and their innovation activities are mainly based on internal knowledge sources. They also cooperate intensively with the advanced users (e.g. companies that acquire machinery components and high-tech instruments produced by specialised-supplier sectors) as well as collaborate other firms to acquire machinery from them (Cantner & Savin, 2014).
(4) Science-based sectors are composed of high-tech industries such as chemicals, electronics, telecommunications and computer related services. Firms operating in this area are generally large and develop product and process innovations internally as well as use external knowledge sources such as universities and research institutes in their R&D activities (Castellacci, 2008). Intellectual property protection in science-based sectors is mainly based on patents, secrecy, and tacit know-how.

Among the Pavitt's sectoral classes, supplier-dominated sectors are least innovative. As discussed above, firms operating in supplier-dominated industries lack internal R&D capabilities and mainly acquire machinery and equipment from other sectors, implying that they are less likely to perform both internal and external R&D. Therefore, supplier-dominated industries are excluded from the analysis. Remaining three sectoral classes

[3] Table 1 (in Appendix) provides more detailed explanation of the revised Pavitt's sectoral taxonomy.

belong to medium- and high-technology industries. Firms in these sectors (e.g. scale-intensive, specialised-supplier and science-based industries) may use both internal and external knowledge sources to generate product and process innovations, but the nature of generated innovations differ across these industries. In particular, technological innovation in scale-intensive sectors is mainly incremental, which is characterized by refinements and modifications in existing products or processes (Cantner & Meder, 2007). In other words, as scale-intensive companies use their technological skills to exploit economies of scale, their innovation activities are directed towards cutting cost and improving of production processes. Therefore, technological innovation in scale-intensive industries is expected to be relatively a low degree of novelty. Contrariwise, innovation activities in specialised-supplier and science-based industries is mainly directed towards generating breakthrough product and technology innovations rather than cost-reducing process innovations. As companies operating in this area often face rapid changes in technology and consumer preferences, they may generate technology innovations with a high degree of novelty than companies from scale-intensive sectors.

Taking into consideration the positive performance implication of internal R&D and R&D outsourcing, one should expect that the joint implementation of these R&D strategies is positively associated with invention performance in specialised-supplier and science-based industries. Contrariwise, this relationship might be limited or less significant in scale-intensive industries. Hence, the following hypothesis is proposed:

> *H2c: the joint implementation of internal R&D and R&D outsourcing is positively and more significantly associated with invention quantity and quality in specialised-supplier and science-based industries than in scale-intensive sectors.*

3 Data description

3.1 Sample

The dataset used in this study comes from the Mannheim Innovation Panel (MIP)[4] database. The MIP, which is the German part of the Community Innovation Survey, has been collected every year since 1993 by the Centre for European Economic Research (ZEW). The target population of the MIP is German innovative firms with at least five employees. The survey gathers detailed information on the innovation activities of the firms, such as the type of innovation partner, expenditures on internal and external R&D, product and process innovation, etc. This dataset is supplemented by patent data obtained from the European Patent Office (EPO) to study the relationship between R&D outsourcing and invention performance. The EPO provides information about the patents

4 The paper acknowledges access to the Mannheim Innovation Panel and patent databases from the Centre for European Economic Research (ZEW).

applied for by German firms at the EPO from 1978 until the end of the data (2011). In particular, I obtain information about the number of patents that German firms applied for at the EPO and the number of forward citations that these patents obtained in subsequent time periods. To have enough time windows to count the patent forward citations, which are used to measure the quality of a patent, the empirical analysis covers two waves (1997, 2001) of the MIP. Although the key interest variables of the study are also identified in other waves of the MIP (e.g. 2005, 2009), these waves cannot be used in the study because of providing not enough time windows for measuring the quality of a patent in terms of counting the patent forward citations. Hence, the pooled cross-sectional dataset are used in the analysis obtained from the 1997 and 2001 surveys of the MIP, which gives information on companies R&D activities during the three years period prior the survey. The sample is restricted to innovative firms, resulting in 4380 observations (2391 for manufacturing and 1989 for service industries, respectively). These observations are distributed across the sectoral classes as follows: 1051 firms come from supplier-dominated sectors, 972 from scale-intensive sectors, 1345 from specialized-suppliers sectors and 768 from science-based sectors. There are 244 companies in the sample which attributed none of the sectoral classes.

3.2 Dependent variables

Two types of dependent variables are considered in the empirical analysis. The first one (INV_N) is the number of patents filed by firm i in period t+3. In other words, INV_N refers to the number of patents that firms are granted in the periods 1998–2000 and 2002–2004, respectively to the 1997 and 2001 surveys (see Table 2 in Appendix). Given that patents vary significantly in terms of their quality and innovative contents (Narin & Olivastro, 1988; Griliches, 1990; Trajtenberg, 1990), as the second dependent variable, I use the average forward citations that a firm's patents obtain in subsequent seven-year windows after the filing year weighted by its patent counts.

3.3 Main explanatory variables

The first explanatory variable used in the econometric analysis is EXT_R&D, which is a binary variable and indicates whether a firm has expenditure in R&D carried out by an external actor not affiliated with the company. The second explanatory variable is INT_R&D, which has a binary outcome and shows whether a firm has investment in R&D undertaken inside its laboratory establishment.

3.4 Control variables

I consider several control variables that might be relevant in the econometric model for invention performance. First, I account for whether a firm has formal innovation cooperation with an external actor; the variable has a binary outcome and it is expressed as R&D_COOP. Cooperation in R&D is seen as an important instrument to acquire skills and specialized know-how from external entities, to minimize the costs and risks of R&D projects and, as a result, to improve the performance of R&D activities (Hagedoorn, 1993). Therefore, I expect a positive relationship between R&D_COOP and the invention performance. Second, to control for the international competition that firms face (Cassiman & Veugelers, 2006; Grimpe & Kaiser, 2010), I introduce the variable EXPORT, which has a binary outcome (1 if a firm has sales from export). As companies competing in global markets often face rapid changes in technology and consumer preferences, they might be more innovative than their counterparts operating only in the local market. In this context, I expect a positive relationship between EXPORT and invention performance. Third, I control for firm location, specifically whether it is in East or West Germany (LOCATION_EAST). Given that there are regional differences between East and West Germany with regard to the infrastructure and economic growth, firms located in East Germany might be lagging behind those located in West Germany in terms of invention performance (Grimpe & Kaiser, 2010).

Furthermore, I account for firms' prior accumulated knowledge in the econometric analysis. It can be expected that those firms that accumulated a high stock of knowledge in time t-1 are more likely to be innovative in period t. In other words, there can be path dependency in invention activities (Nelson & Winter, 1982; Cyert & March, 1992). Therefore, I introduce the PRE_INV_N and PRE_INV_Q variables into the regression models to control for path dependency in the invention performance. PRE_INV_N refers to the pre-sample patent counts in the five-year period. Given that the sample includes the 1997 and 2001 surveys and each survey contains information about the innovation activities of the firms during the three years period prior the survey (for instance, the 1997 survey provides information about the firms' innovation activities in the period 1994–1996), PRE_INV_N stands for patent counts in the period 1989–1993. To account for the quality of these pre-sample patents, I take the average forward citations that firms' pre-sample patents obtain in subsequent seven-year windows after the filing year weighted by their pre-sample patent counts (PRE_INV_Q). In the econometric models, the variables PRE_INV_N and PRE_INV_Q are introduced in logarithmic values. Given that some firms do not have any patent or forward patent citations, the logarithmic transformation of these variables results in missing values. To deal with this issue, I set the value to zero for the missing values (LOG (PRE_INV_N) = 0 if PRE_INV_N = 0) and introduce an additional dummy variable (zero for patent values and one for non-patent values; the same applies to average forward patent citations) (Beneito, 2006; Grimp & Kaiser, 2010).

Moreover, to control for firm unobserved characteristics, I introduce firm size and industry dummy variables. Firm size is measured as the number of employees transformed into logarithmic values (LOG_SIZE).

4 Econometric methods

As the first dependent variable (INV_N) used in the empirical analysis has non-negative count outcomes (denoted by y, y ={0,1,2,….}), I use count data methods to analyse the sample. The starting point of count data analysis is a Poisson model (Cameron & Trivedi, 2005, 2009), which is considered to be an appropriate econometric method when the variance and the mean of the dependent variable have equal values (referred to as an equal-dispersion property), which is often violated in an applied work due to the over-dispersion problem (Cameron & Trivedi, 2009). The standard method to cope with the over-dispersion problem is to use a negative binomial model, which preserves the mean and increases the variance. As the variance exceeds the mean in the dependent variable and, hence, there is an over-dispersion problem in the data, I used the negative binomial model in the econometric analysis.

The second variable (INV_Q) used in the analysis is the ratio of forward patent citations to patent counts. Given that the dependent variable contains decimal numbers, the count data models are inappropriate in this case. To account for the specific feature of the data, a generalized linear model (GLM) is used in the econometric analysis (Nelder & Wedderburn, 1972). The GLM is flexible and has the power to model the data with ratio and non-normal distributions when a proper family distribution and link function are defined in the model. I use the GLM with a gamma family distribution and a log link, because the variance exceeds the mean in the dependent variable. I also introduce a robust option into the model to obtain robust standard errors if the family distribution is incorrectly specified.

5 Estimation results

Considering the total sample (manufacturing and service firms together), Table 4 (in Appendix) shows that R&D outsourcing (EXT_R&D) is significantly and positively associated with invention quantity (INV_N). The result, which is in line with the H1a hypothesis, suggests that those firms outsourcing some parts of their R&D activities to external entities are more innovative than their counterparts that do not invest in this R&D strategy. This might be related to the fact that R&D outsourcing can help firms to focus on the activities that they can perform best and to use the services of external actors for tasks in which they lack expertise. As a result, this strategy can support firms to improve their R&D performance. Moreover, the data analysis indicates that there is a significant positive relationship between internal R&D (INT_R&D) and invention quantity (INV_N), implying that those firms that carry out R&D internally generate more inventions than other companies that do not invest in in-house R&D activities. Generally speaking, internal R&D is considered to be a key source for enhancing the learning process within a firm and developing new products and technologies. As expected, the interaction term of internal R&D and R&D outsourcing is also significantly and positively associated with invention quantity. Hence, in line with my H2a hypothesis, the empirical analysis indicates that those companies using both internal and external knowledge sources in R&D activities displace better invention performance (in terms of invention quantity) than their counterparts relying only a single R&D strategy whether it is internal R&D or R&D outsourcing.

Furthermore, Table 5 (in Appendix) displays that there is a significant positive relationship between internal R&D and invention quality, but surprisingly neither R&D outsourcing nor the interaction between internal R&D and R&D outsourcing is significantly associated with invention quality. This may suggests that to understand clearly the invention performance of R&D outsourcing, it might be necessary to study the returns of this strategy more specifically in relation to whether R&D is sourced from suppliers, consulting companies or research institutions.

Looking at the sectoral patterns of R&D activities, the empirical results indicate that companies operating in science-based industries are more likely to employ the R&D outsourcing strategy to improve their invention performance (in terms of invention quantity as well as quality) comparing to firms coming from scale-intensive and specialized-supplier sectors (see Table 4 and 5 in Appendix). For scale-intensive sectors, R&D outsourcing is slightly significant and positive for invention quantity, but the variable is non-significant for invention quality. In a somewhat similar way, this R&D strategy presents a significant sign neither for invention quantity nor for invention quality when considering specialized-supplier industries alone. Contrariwise, internal R&D is the major source of technology for specialized-supplier sectors. Hence, firms operating in specialized-supplier sectors are more likely to show better invention performance (including invention quantity as well as quality) when they organize R&D activities internally rather than externally. For science-based industries, internal R&D is also significantly and positively related to invention quality, but surprisingly the variable is non-significant for invention quantity. This non-significant relationship between internal R&D and invention quantity might be partly due to the fact that the expenditures for internal R&D are not differentiated among basic, applied or developing activities.

For all sectoral classes (e.g. scale-intensive, specialized-supplier and science-based industries), surprisingly the joint implementation of internal and external R&D strategies presents a non-significant sign for invention quantity as well as for invention quality. To put it another way, the empirical results provide no evidence that firms coming from specialized-supplier and science-based industries are more likely to employ both internal R&D and R&D outsourcing strategies to innovate than their counterparts operating in scale-intensive sectors.

Furthermore, the study shows that manufacturing firms are more likely to combine internal and external knowledge sources in their invention activities comparing to service companies. In particular, the results indicate that the joint implementation of internal R&D and R&D outsourcing is significant and positive for invention quantity when I consider the manufacturing sector alone, while for the service sector it is not the case (see Table 6 in Appendix). This might be related to the fact that firms operating in the manufacturing industry experience strong approriability conditions comparing to companies coming from the service industry. Therefore, manufacturing firms are more likely to explore both internal and external R&D strategies in their innovation activities comparing to service companies. Besides that, considering the manufacturing sector alone, Table 6 (in Appendix) shows that internal R&D is significantly and positively associated with invention quality, but the significance level of the coefficient is lower for invention quantity. In contrast, R&D outsourcing is only significant and positive for invention quantity, but the variables present non-significant signs for invention quality. If I consider the service sector alone, there is a significant positive relationship between internal R&D and invention quantity as well as between R&D outsourcing and invention quantity, but both R&D strategies are non-significant for invention quality.

Having discussed the relationship between the main explanatory variables and invention performance, I shift my attention to the control variables used in the econometric analysis. Considering manufacturing and service sectors together as well as separately, the results show that R&D cooperation (R&D_COOP) is significantly and positively related to invention quantity, but it presents a non-significant coefficient for invention quality. This could be explained by the fact that for invention quality, not only cooperating with external actors in R&D, but also with whom this cooperation takes places, whether it is research institutions, suppliers, customers, etc. may be important.

Furthermore, the data analysis shows that past invention activities matter only for invention quantity but not for invention quality if I consider the total sample (manufacturing and service sectors together) and manufacturing sector alone. This might be due to the fact that the number of forward citations, which is used as an indicator of patent quality, depends on whether a firm's patent attributes technological knowledge of citing firms and their absorptive capacity (Hottenrott & Lopes-Bento, 2012).

Regarding export intensity (EXPORT) and firm size (LOG_SIZE), the variables are significantly and positively related to invention quantity as well as to invention quality. Besides that, there is a significant negative relationship between LOCATION_EAST and invention quantity, but LOCATION_EAST is non-significant for invention quality. However, the variable presents a significant and negative sign for invention quality for all sectoral classes (see Table 5 in Appendix). In general, as prior research also suggests (Grimpe & Kaiser, 2010), West German firms are more innovative than their counterparts located in East Germany.

6 Conclusion

The question of whether firms experience 'gains' or 'pains' from R&D outsourcing is a subject of ongoing research in the R&D management literature. A number of previous papers discuss this issue, yet little is known about how this strategy relates to the value of an outsourcer firm's research output. Motivated by this research gap in the literature, this study further discusses the prior research findings and provides new insights into the relationship between R&D outsourcing and invention performance (in terms of patent quantity as well as quality). In particular, considering manufacturing and service sectors together as well as separately, the empirical results show that those firms that outsource some R&D functions generate more inventions than their counterparts that do not invest in this R&D strategy. Given that R&D outsourcing allows firms to contract out R&D activities in which they do not possess high-class expertise and to concentrate on the activities that they can perform best, such inter-firm task division may help companies to devote their financial and human resources to their key research activities and, as a result, to improve the efficiency and effectiveness of their invention activities. Hence, the research suggests that firms can improve the invention performance of their R&D activities by outsourcing some R&D functions to external actors. In this context, policymakers should stimulate the inter-firm division of R&D labour among service and manufacturing companies to boost invention activities in the country. However, the data analysis indicates a non-significant relationship between R&D outsourcing and invention quality. This could be explained by the fact that for invention quality, not only using the R&D outsourcing strategy in innovation activities, but also with whom this collaboration takes places can be important. Hence, to understand clearly the invention performance of R&D outsourcing, it might be necessary to study the returns of this strategy more specifically in relation to whether R&D is sourced from suppliers, consulting companies or research institutions. In contrast to R&D outsourcing, internal R&D is significantly and positively associated with invention quality, implying that those companies that carry out R&D internally generate more inventions than other firms that do not invest in this R&D strategy. Chesbrough (2003) suggests that internal R&D has lost its strategic significance and companies have shifted their innovation activities from internal to external R&D, but the data analysis indicates that internal R&D is important innovative input to generate high quality inventions. This suggests that relying heavily on external R&D may hamper firms' innovation performance. Instead, the degree of R&D openness in innovation should be in balance with the internal R&D activities, which can help firms to gain from external R&D and to enhance their innovation performance.

The data analysis also shows that there are significant inter-industry differences the way in which firms organize their R&D activities. In particular, the research reveals that firms operating in science-based industries are more likely to employ the R&D outsourcing strategy to improve their invention performance (in terms of invention quantity as well as quality) comparing to companies coming from scale-intensive and specialized-supplier sectors. In other words, R&D outsourcing or external R&D is the important source of innovation for science-based companies. In contrast, internal R&D is the major source of technology in specialized-supplier sectors, implying that firms coming from specialized-supplier sectors displays better invention performance (including invention quantity as well as quality) when they organize R&D activities internally rather than externally. In science-based industries, internal R&D is also significant and positive for invention quality, but surprisingly the variable is non-significant for invention quantity. This non-significant relationship between internal R&D and invention quantity in science-based industries might be partly due to the fact that the expenditures for internal R&D are not differentiated among basic, applied or developing activities.

Furthermore, the study shows that manufacturing firms are more likely to combine internal and external R&D strategies in their invention activities comparing to service companies. Given that appropriability conditions are stronger in manufacturing rather than in service sectors, manufacturing companies are more likely to explore both internal R&D and R&D outsourcing strategies to enhance their invention performance. However, the joint implementation of these R&D instruments presents a non-significant sign for invention quality. Besides that, considering the sectoral classes separately (e.g. scale-intensive, specialized-supplier and science-based industries), the interaction between internal R&D and R&D outsourcing is neither significant for invention quantity nor for invention quality. Due to data limitations, I could not examine what factors prevent companies from achieving a positive performance outcome through combining internal and external R&D strategies.

The paper also suffers from other limitations that offer interesting avenues for future research. First of all, future study should examine the differences in the innovative performance of domestic and international R&D outsourcing. Second, further research is required to understand how different types of R&D outsourcing relationships, such as short- and long-term contracts, affect a client firm's invention performance. It could be also interesting to study what kinds of managerial practices and governance modes should be used to maximize the returns of the R&D outsourcing strategy.

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8 Appendix

Table 1. Revised Pavitt's sectoral taxonomy - Source: Cantner and Savin (2014)

Sector classification	Industry	NACE 2-digit
Supplier-dominated industries	Food products and beverages	15
	Tobacco products	16
	Textiles	17
	Wearing apparel; dressing and dyeing of fur	18
	Leather and leather products	19
	Wood and wood products	20
	Pulp, paper and paper products	21
	Publishing, printing and reproduction of recorded media	22
	Furniture, jewellery, musical instruments manufacturing	36
	Recycling	37
	Sale, maintenance and repair of motor vehicles and motorcycles	50
	Wholesale trade and commission trade, except of motor vehicles	51
	Retail trade, except of motor vehicles, repair of personal and household goods	52
	Hotels and restaurants	55
	Land transport, transport via pipelines	60
	Water transport	61
	Air transport	62
	Supporting and auxiliary transport activities	63
Scale-intensive industries	Rubber and plastic products	25
	Other non-metallic mineral products	26
	Basic metals	27
	Fabricated metal products, except machinery and equipment	28
	Motor vehicles, trailers and semi-trailers	34
	Other transport equipment (ships, railway, aircraft, spacecraft)	35
	Financial intermediation, except insurance and pension funding	65
	Insurance and pension funding, except compulsory social security	66
	Activities auxiliary to financial intermediation	67
Specialized-supplier industries	Machinery and equipment (including weapons, ammunition, domestic appliances)	29
	Medical, precision and optical instruments, watches and clocks	33
	Real estate activities	70
	Renting of machinery, equipment, personal and household goods	71
	Other business activities (incl. legal, accounting, book-keeping)	74
Science-based industries	Coke, refined petroleum products and nuclear fuel	23
	Chemicals and chemical products	24
	Office machinery and computers	30
	Electrical machinery and apparatus	31
	Radio, television and communication equipment	32
	Post and telecommunications	64
	Computer and related activities	72
	Research and development	73

Table 2. Descriptive statistics

Variable names	Variable definition	Obs.	Mean	Std. dev.	Min.	Max.
INV_N	Patent counts in the periods 1998–2000 and 2002–2004, respectively to the 1997 and 2001 surveys	4380	0.914	7.114	0	254
INV_Q	The average forward citations that the firm's patents obtain in subsequent seven-years windows after the filing year	4380	0.424	3.961	0	121
EXT_R&D	Binary: 1 if a firm outsources R&D activities	4380	0.292	0.455	0	1
INT_R&D	Binary: 1 if a firm invests in internal R&D	4380	0.572	0.494	0	1
R&D_COOP	Binary: 1 if a firm has R&D cooperation with an external actor	4380	0.273	0.445	0	1
EXPORT	Binary: 1 if a firm has sales from export	4380	0.533	0.498	0	1
LOCATION_EAST	Binary: 1 if a firm is located in East Germany	4380	0.340	0.473	0	1
PRE_INV_N (logs)	Pre-sample patents in the period 1989–1993	4380	0.127	0.540	0	5.568
PRE_INV_N (d)	Binary: 0 for patent values and 1 for non-patent values	4380	0.893	0.308	0	1
PRE_INV_Q (logs)	Average forward patent citations obtained for the pre-sample patents in the seven years after the filing year	4380	0.089	0.498	-2.484	6.089
PRE_INV_Q (d)	Binary: 0 for patent citation values and 1 for non-citation values	4380	0.924	0.264	0	1
LOG_SIZE	Firm employees in logarithmic values	4380	4.470	1.745	0	13.009

Table 3. Correlation table

	Variable names	1	2	3	4	5	6	7	8	9	10	11	12
1	INV_N	1.000											
2	INV_Q	0.144***	1.000										
3	EXT_R&D	0.112***	0.080***	1.000									
4	INT_R&D	0.073***	0.065***	0.377***	1.000								
5	R&D_COOP	0.092***	0.049***	0.295***	0.235***	1.000							
6	EXPORT	0.079***	0.089***	0.231***	0.324***	0.149***	1.000						
7	LOCATION_EAST	-0.068***	-0.069***	-0.065***	-0.048***	0.007	-0.200***	1.000					
8	PRE_INV_N (logs)	0.419***	0.154***	0.139***	0.119***	0.124***	0.166***	-0.135***	1.000				
9	PRE_INV_N (d)	-0.294***	-0.157***	-0.171***	-0.159***	-0.126***	-0.244***	0.177***	-0.522***	1.000			
10	PRE_INV_Q (logs)	0.262***	0.108***	0.109***	0.080***	0.075***	0.146***	-0.095***	0.458***	-0.516***	1.000		
11	PRE_INV_Q (d)	-0.324***	-0.130***	-0.154***	-0.131***	-0.115***	-0.203***	0.154***	-0.531***	0.521***	-0.522***	1.000	
12	LOG_SIZE	0.206***	0.119***	0.232***	0.125***	0.177***	0.211***	-0.228***	0.285***	-0.284***	0.169***	-0.273***	1.000

Note: *, ** and *** denote significance at the 10%, 5% and 1% level, respectively. Standard errors are in parentheses.

Table 4. Results for invention quantity (manufacturing and service sectors together)

	Invention quantity (INV_N)							
	Negative binomial models							
	Manufacturing and service firms							
	Total sample		Scale-intensive industries		Specialized-supplier industries		Science-based industries	
	1	2	3	4	5	6	7	8
EXT_R&D	0.509***	-0.354	0.466*	0.080	0.028	-0.809	1.109***	0.018
	(0.128)	(0.350)	(0.257)	(0.625)	(0.190)	(0.577)	(0.286)	(1.018)
INT_R&D	0.619***	0.460***	0.447	0.360	0.607***	0.472*	0.211	0.053
	(0.140)	(0.151)	(0.275)	(0.303)	(0.225)	(0.241)	(0.354)	(0.377)
R&D_COOP	0.497***	0.483***	0.539**	0.526**	0.142	0.132	0.455*	0.419
	(0.121)	(0.121)	(0.256)	(0.258)	(0.182)	(0.182)	(0.259)	(0.261)
EXPORT	1.001***	0.989***	1.517***	1.516***	1.408***	1.399***	0.538*	0.547*
	(0.145)	(0.145)	(0.315)	(0.316)	(0.230)	(0.230)	(0.286)	(0.285)
LOCATION_EAST	-0.478***	-0.466***	-0.455	-0.448	-0.165	-0.174	-0.044	-0.050
	(0.144)	(0.144)	(0.306)	(0.307)	(0.233)	(0.233)	(0.312)	(0.311)
PRE_INV_N (logs)	0.460***	0.448***	0.585***	0.577***	0.530***	0.516***	0.213	0.217
	(0.097)	(0.098)	(0.208)	(0.210)	(0.125)	(0.127)	(0.191)	(0.191)
PRE_INV_N (d) (no pre-sample inventions)	-1.802***	-1.815***	-1.165***	-1.182***	-1.553***	-1.596***	-2.351***	-2.307***
	(0.182)	(0.183)	(0.398)	(0.400)	(0.227)	(0.231)	(0.427)	(0.426)
LOG_SIZE	0.497***	0.497***	0.559***	0.561***	0.625***	0.617***	0.459***	0.457***
	(0.036)	(0.036)	(0.087)	(0.087)	(0.061)	(0.060)	(0.068)	(0.068)
EXT_R&D*INT_R&D		0.994***		0.462		0.931		1.187
		(0.375)		(0.688)		(0.609)		(1.065)
INTERCEPT	-3.916***	-3.786***	-5.148***	-5.098***	-4.577***	-4.404***	-2.720***	-2.637***
	(0.365)	(0.367)	(0.718)	(0.722)	(0.490)	(0.499)	(0.590)	(0.594)
Industry dummy	YES	YES	YES	YES	YES	YES	YES	YES
Obs.	4380	4380	972	972	1345	1345	768	768
LR chi2	1061.01	1068.01	240.77	241.21	490.62	492.88	208.61	209.85
Prob>chi2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Note: *, ** and *** denote significance at the 10%, 5% and 1% level, respectively. Standard errors are in parentheses.

Table 5. Results for invention quality (manufacturing and service sectors together)

	Invention quality (INV_Q)							
	Generalized linear models							
	Manufacturing and service firms							
	Total sample		Scale-Intensive industries		Specialized-Supplier industries		Science-Based industries	
	1	2	3	4	5	6	7	8
EXT_R&D	0.609	-0.392	0.485	-0.002	0.019	-1.686	0.814**	1.076
	(0.379)	(0.633)	(0.480)	(0.765)	(0.472)	(1.221)	(0.380)	(1.136)
INT_R&D	1.447***	1.288***	0.121	0.018	1.179**	1.020**	0.883**	0.944**
	(0.396)	(0.440)	(0.399)	(0.446)	(0.469)	(0.506)	(0.438)	(0.439)
R&D_COOP	-0.086	-0.097	-1.037**	-1.040**	-0.166	-0.201	0.684*	0.697**
	(0.322)	(0.317)	(0.418)	(0.419)	(0.390)	(0.395)	(0.362)	(0.350)
EXPORT	2.520***	2.557***	3.387***	3.370***	2.623***	2.580***	1.294***	1.292***
	(0.494)	(0.492)	(0.672)	(0.656)	(0.635)	(0.628)	(0.439)	(0.440)
LOCATION_EAST	-0.415	-0.454	-1.681***	-1.669***	-1.543***	-1.527***	-1.190*	-1.187*
	(0.517)	(0.507)	(0.511)	(0.506)	(0.394)	(0.397)	(0.708)	(0.708)
PRE_INV_Q (logs)	-0.107	-0.079	0.005	0.002	0.043	0.059	0.036	0.033
	(0.219)	(0.227)	(0.200)	(0.198)	(0.211)	(0.212)	(0.182)	(0.182)
PRE_INV_Q (d) #	-1.801***	-1.753***	-0.727	-0.724	-0.753*	-0.729*	-0.967**	-0.978**
	(0.497)	(0.505)	(0.453)	(0.448)	(0.385)	(0.387)	(0.450)	(0.450)
LOG_SIZE	0.938***	0.939***	0.518***	0.520***	0.716***	0.718***	0.488***	0.490***
	(0.114)	(0.114)	(0.107)	(0.107)	(0.138)	(0.141)	(0.122)	(0.123)
EXT_R&D*INT_R&D		1.161		0.571		1.789		-0.288
		(0.780)		(0.952)		(1.314)		(1.188)
INTERCEPT	-7.697***	-7.647***	-5.994***	-5.940***	-6.657***	-6.530***	-5.181***	-5.229***
	(0.974)	(0.977)	(1.122)	(1.096)	(1.250)	(1.262)	(1.130)	(1.149)
Industry dummy	YES	YES	YES	YES	YES	YES	YES	YES
Obs.	4380	4380	972	972	1345	1345	768	768
Log pseudo-likelihood	9837.6	9904.3	-545.2	-544.5	-917.4	-913.9	-464.7	-464.6

Note: *, ** and *** denote significance at the 10%, 5% and 1% level, respectively. Standard errors are in parentheses.
no pre-sample patent forward citations

Table 6. Results for invention quantity and quality

	Invention quantity (INV_N)				Invention quality (INV_Q)			
	Negative binomial models				Generalized linear models			
	Only manufacturing firms		Only service firms		Only manufacturing firms		Only service firms	
	1	2	3	4	5	6	7	8
EXT_R&D	0.384***	-0.329	0.861**	-0.405	0.609	-0.392	-0.225	-0.372
	(0.134)	(0.375)	(0.392)	(0.875)	(0.379)	(0.633)	(0.596)	(0.602)
INT_R&D	0.304*	0.168	0.820**	0.601	1.447***	1.288***	0.864	0.734
	(0.156)	(0.170)	(0.387)	(0.409)	(0.396)	(0.440)	(0.693)	(0.725)
R&D_COOP	0.420***	0.402***	0.716*	0.721*	-0.086	-0.097	0.505	0.483
	(0.127)	(0.127)	(0.372)	(0.373)	(0.322)	(0.317)	(0.610)	(0.603)
EXPORT	0.800***	0.792***	0.782**	0.773**	2.520***	2.557***	1.804***	1.780***
	(0.188)	(0.187)	(0.332)	(0.334)	(0.494)	(0.492)	(0.550)	(0.546)
LOCATION_EAST	-0.459***	-0.449***	-0.295	-0.269	-0.415	-0.454	-0.691	-0.699
	(0.162)	(0.163)	(0.362)	(0.363)	(0.517)	(0.507)	(0.900)	(0.904)
PRE_INV_N (logs)	0.520***	0.506***	0.260	0.287				
	(0.092)	(0.093)	(0.459)	(0.477)				
PRE_INV_N (d) #1	-1.418***	-1.441***	-2.585***	-2.491***				
	(0.181)	(0.182)	(0.745)	(0.754)				
PRE_INV_Q (logs)					-0.107	-0.079	-0.222	-0.217
					(0.219)	(0.227)	(0.212)	(0.208)
PRE_INV_Q (d) #2					-1.801***	-1.753***	-2.650***	-2.634***
					(0.497)	(0.505)	(0.588)	(0.581)
LOG_SIZE	0.507***	0.506***	0.507***	0.516***	0.938***	0.939***	0.500***	0.495***
	(0.045)	(0.045)	(0.090)	(0.092)	(0.114)	(0.114)	(0.145)	(0.143)
EXT_R&D*INT_R&D		0.813**		1.552		1.161		0.384
		(0.402)		(0.951)		(0.780)		(0.767)
INTERCEPT	-6.095***	-5.972***	-4.411***	-4.318***	-7.697***	-7.647***	-5.637***	-5.488***
	(0.521)	(0.523)	(1.366)	(1.378)	(0.974)	(0.977)	(2.081)	(2.074)
Industry dummy	YES	YES	YES	YES	YES	YES	YES	YES
Obs.	2391	2391	1989	1989	2391	2391	1989	1989
LR chi2	766.56	770.52	173.22	175.94				
Prob>chi2	0.0000	0.0000	0.0000	0.0000				
Log pseudo-likelihood					9837.6	9904.3	-318.2	-316.3

Note: *, ** and *** denote significance at the 10%, 5% and 1% level, respectively. Standard errors are in parentheses.
#1 no pre-sample inventions.
#2 no pre-sample patent forward citations.