RIETI Discussion Paper Series 11-E-038

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RIETI Discussion Paper Series 11-E-038
April 2011

Exploring the Sources of Firm-level Scale Economies in R&D: Complementary assets, internal and external knowledge inflows, and inventor team size[1]

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Abstract

This paper explores the sources of firm-level scale economies in R&D, based on unique project-level data from a new large-scale survey of Japanese inventors, matched with firm-level data. We focus on four sources: complementary assets, internal and external knowledge inflows, and inventor team size. Major findings include: (1) a larger firm tends to generate more patents from a research project but not more valuable patents, controlling for the objectives and the R&D investment (inventive efforts) for the project; (2) the sales of a firm rather than its R&D (or patent stocks) significantly affects the number of patents from the project, suggesting that the main source of such scale economy is not internal knowledge inflow but “appropriation advantage” of a large firm; (3) an inventor in a large firm often gains important knowledge for the project from internal knowledge inflow as well as from scientific literature. However, the performance of R&D—for which internal knowledge is important—tends to be low; and (4) the size of inventor teams increases with firm size and technological diversity. A larger team size is significantly associated with higher patent value and, as such, the size of the inventor team is one source of firm-level scale economies.

Keywords: R&D, invention, scale, knowledge, complementary assets, and team.
JEL Classification: O31; O32; L25

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[1] We would like to thank Masahisa Fujita, Kozo Oikawa, Morikawa Masayuki, Bronwyn Hall and the members of RIETI’s research team on R&D. In particular, we appreciate Masahisa Fujita’s suggestion to our research, i.e., focusing on skill diversity represented by size of the inventor team.

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1 Introduction

This paper explores the sources of firm level scale economies in R&D by exploiting the newly collected detailed project level information. A pioneering study by Henderson and Cockburn (1996) demonstrated that there is significant economies of scale and scope at the firm level for drug discovery, even though there may look to exist a decreasing return in research on patent outputs at firm level data (see Henderson and Cockburn (2001)). That is, they have successfully identified firm level scale economy by exploiting project level information. This paper follows a similar strategy and explores the sources of scale and scope economies (for brevity we call “scale economies”) , focusing on complementary assets, internal and external knowledge inflows and inventor team size. There are three novel points in our empirical analysis. First, we aim at identifying both the scale economy in the R&D task itself and the appropriation advantage of a large firm, based on complementary assets. Although past studies often use patents as an output measure of R&D, they are actually the result of the choices by a firm as to seeking patent application vs. relying on secrecy or on defensive publication, so that patenting is endogenous. The studies such as by Hall and Ziedonis (2001) find that the patenting behavior of firm is more positively related with the size of tangible assets than with R&D investment, which might reflect the appropriation advantage of a large firm (or the defensive motivation against the risk of being held up). Thus, large firms’ apparent superior performance in patenting may not be due to its superior R&D performance but due to its advantage in appropriating the return from its inventions.

Second, we measure internal and external knowledge spillover to the R&D project directly, which will help us identifying how firm size may affect the strength of such knowledge inflows. One potentially important mechanism for scale advantage is internal knowledge flow among R&D projects within a firm. Such inflows may take place concurrently and from past projects to current projects through accumulated internal knowledge stock (see for an example, Henderson and Cockburn (1996)) . The past studies attempted to measure the internal inflow indirectly by looking at how the performance of a R&D project is related to the current R&D at firm level and to the stocks of patent grants to the firm. However, such approach is vulnerable to the existence of uncontrolled technological opportunities or demand side shocks which affect the value of the entire R&D portfolio of a firm. Another important source of scale advantage of a large firm is its higher absorptive capability with respect to external knowledge (Cohen and Levinthal (1989) and Gambardella (1992)). The empirical studies also look at how the R&D performance of a firm is related to the patents and R&Ds of the other firms located closely in technological space (Jaffe (1986) and Henderson and Cockburn (1996)). However, such approach may also be vulnerable to the existence of uncontrolled technological opportunities or demand side shocks which affect all firms in the same technological sector. For an example, when an important scientific discovery becomes available, it will increase patenting across firms in the relevant technology field. We will use directly the inventor's evaluation of the importance of knowledge inflows to the R&D project in order to mitigate this problem of measuring internal knowledge inflow. We will then assess how they are related to firm characteristics[2].

Third, we will assess how firm size matter as a determinant of inventor team size. As invention process becomes more complex, the number of co-inventors has increased (see Jones (2009)). Then, one potential important source of scale advantage of a firm is a larger pool of inventors within a firm, which can provide more variety of expertise and experiences. We will assess whether a large firm uses a larger inventor team for the same type of a research project and whether a larger size of inventors contributes to enhancing the research performance,

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[2] An alternative approach would be to use citation information, which is however subject to significant since substantial part of references are chosen by non-inventors such as examiners (see Nagaoka, Motohashi and Goto for a review (2011)).

controlling for the total man months spent by the researchers of the project as a whole.

For our analysis of project level data, it is important to specify the basic characteristics of R&D project in detail, since they are heterogeneous in terms of the objectives and the stages, the distributions of which can vary across firms. The project aiming at strengthening the competitiveness of the core business of a firm may be quite different from those for the project for developing new business or cultivating new technical seeds. The scope of an R&D project varies across firms. Some firms may engage in a fully integrated project, covering basic research to development, while the others may focus on a particular stage and outsource the other stages. Patenting propensity may differ between product innovation and process innovation. The input to the R&D process is also diverse: number of inventors, input of researcher time, calendar time and knowledge inflows.

We use the data from the survey over Japanese inventors implemented in 2007, which provide performance data on the R&D project which yielded the focal patent as well as their detailed characteristics, in order to characterize R&D project in detail. The questionnaire identified not only the knowledge sources for the conception of the research project but also the business objectives of such project, its scope in the R&D stages and the type in terms of product development vs. process development[3]. It identifies both the number of patents from the project as well as the economic value of the surveyed patent evaluated by the inventor himself as performance indicators. We also obtained a man-month measure for each project, in addition to the number of inventors. The project information has been matched to the firm-level financial and patent data for the applicant firms. We also constructed the patent stock data for listed firms (large firms). The dataset allows us to assess the effects of project-level and firm-level characteristics on the R&D performance, recognizing the heterogeneity of R&D projects.

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[3] Product innovation in the RIETI survey does not be limited to the drastic innovation replacing the existing product.

The rest of the paper is organized as follows. Section 2 provides theoretical framework. Section 3 provides an explanation of the data and descriptive statistics. Section 4 provides estimation models and section 5 presents the estimation results. Section 6 concludes and discusses the implications.

2. Theoretical framework and hypotheses

2.1 A Model

We consider the following simple model of R&D of a firm with an endogenous patenting decision. We denote the research objective and the research stage of an R&D project j by ω_j (vector) and the importance of internal and external knowledge inflows to the conception of the project by θ_j (vector). The combination of these two variables characterizes an R&D project. We then denote the size of complementarity assets of a firm by A and the R&D supply side capability (such as firm-level knowledge stock, firm-level concurrent R&D, the absorptive capability and the size of the pool of inventors) by K. If the knowledge of the concurrent and past R&D projects can be profitably used for the current project, there is a firm scale economy (As shown Panzar and Willig (1981), the existence of shared input is the source for the economy of scope). We assume that the basic characteristics of an R&D project and the firm characteristics variables affect the level of knowledge inflow to the project.

$$\theta_j = f(\omega_j, K, \delta_j) \qquad (1),$$

where δ_j is a stochastic variable.

Denoting the R&D effort by a firm for project j by x_j (the number of inventors and man months), it gets the following number (z_j) of potentially patentable inventions from the research project:

$$z_j = z(x_j; \omega_j, \theta_j, K, \varepsilon_j) \qquad (2),$$

where ε_j is a stochastic variable. The number of inventions from a project increases with x_j, given the type of project specified by the combination of ω_j and θ_j. That is, $\partial z_j / \partial x_j > 0$. If the firm level knowledge stock enhances the R&D productivity in terms of the number of inventions, the number of inventions from a project also increases with K. $\partial^2 z_j / \partial x_j \partial K$ may be positive or negative, depending on whether the exhaustion is more important than the cumulative gain from technology development within a firm.

We denote the quality of invention *i* from the project *j* in terms of its expected economic value by $q_{i,j}$ (Without loss of the generality, we assume that the inventions are ordered by the level of the quality). It is randomly given from the value distribution. The distribution of the quality of inventions will be generally be affected by the level of R&D effort x_j of a firm for the project. Higher R&D expenditure would increase the value of the most valuable patents further, while it would also increase the supply of low quality inventions due to the exhaustion of valuable inventions, so that the mean quality may increase or decrease (Lanjouw and Schankerman (2004) presents a model assuming the constancy of the mean quality).

$$q_{i,j} = g(x_j; \omega_j, \theta_j, K_t, \eta_{i,j}) \qquad (3)$$

where $\eta_{i,j}$ is a stochastic variable.

We assume that a firm can capture $m(A)$ of $q_{i,j}$ for its profit where A represents the size or scope of complementary assets the firm possess. $m(A)$ increases with A. The firm patents such invention only if it is not less than the cost of patenting (*g* per invention).

$$m(A) q_{i,j} \geq g \qquad (4)$$

a firm with larger complementary assets seeks for a patent even for a low quality invention and the total number of patents it obtains from a project also increases.

$$n_j = n(x_j;\omega_j,\theta_j,K,A,\mu_j) \qquad (5),$$

where μ_j is a stochastic variable and we have

$$\partial n_j / \partial A > 0 \ . \qquad (6)$$

If we denote the threshold quality satisfying condition (4) as an equality by $q_{thre,j}(A)$,

$$\partial q_{thre,j}(A)/\partial A < 0 \qquad (7)$$

Since we have more inventions for a larger inventive effort, we have

$$\partial n_j / \partial x_j > 0 \qquad (8)$$

A firm chooses R&D effort x_j so as to maximize the following expected profit from the project:

$$\pi(x_j;\omega_j,\theta_j,K,A,g) = m(A)\sum_{i=1\sim n_j} q_{i,j} - c(x,K) - n_j g \qquad (9)$$

We take into account that the cost of R&D effort for a project depends on the firm scale (*K*), since a large firm may have elastic supply of inventors and a pool of inventors with diverse specializations. The marginal cost of R&D effort rises as R&D effort increases

$$\partial c/\partial x_j > 0 \text{ and } \partial^2 c/\partial {x_j}^2 > 0 \qquad (10).$$

We also assume that the marginal revenue declines with the R&D effort.

$$\partial\{m(A)\sum_{i=1\sim n_j} q_{i,j}\}/x_j > 0 \quad \text{and} \quad \partial^2\{m(A)\sum_{i=1\sim n_j} q_{i,j}\}/{x_j}^2 < 0 \qquad (11)$$

The optimal choice of R&D effort by is given by

$$x_j^* = h(\omega_j,\theta_j,K,A;g) \qquad (12)$$

A firm implements a project only if it expects a positive profit for the optimal size of the R&D

effort.

$$\pi(x_j^*;\omega_j,\theta_j,K,A,g)\geq 0 \qquad (13).$$

From assumptions (10) and (11), we have

$$\partial x_j^*/\partial A>0$$

This induced expansion of the R&D effort will increase the quality of infra-marginal patented inventions and also the supply of the patented inventions with the threshold quality. However, controlling for this, the increase of the size of complementary assets (*A*) reduces the quality of a randomly selected patented invention, since it increases the chance that a lower quality invention is patented due to a lower threshold.

2.2 Main hypotheses

Based on the above framework, we can state the following six hypotheses on the source of the scale economies of a large firm in R&D.

Hypothesis 1 on complementary assets

If a larger size of complementary assets of a firm enhances the expected appropriation, we would observe higher R&D productivity in terms of the number of patents for a project located in a firm with larger complementary assets. At the same time, we would observe a lower value of a patent randomly selected from such a project.

Hypothesis 2 on internal knowledge inflow

If internal knowledge inflow is an important source of scale economies, an inventor in a large firm recognizes higher importance in such knowledge inflows as the source of the conception of the R&D project and such inflow is associated with higher R&D productivity in terms of the number of patents for a project and/or in the value of a patent.

Hypothesis 3 on external knowledge inflow

If external knowledge inflow is an important source of scale economy, an inventor in a large firm recognize higher importance in such knowledge inflow as the source of the conception of the R&D project and such inflow is associated with higher R&D productivity in terms of the number of patents for a project and/or in the value of a patent.

Hypothesis 4 on size of inventor team

If the size of inventor team is an important source of scale economy, a large firm promotes the formation of a large inventor team and large size of inventor team enhances the R&D performance.

3. Data and descriptive statistics

We use the novel dataset from the survey of Japanese inventors implemented by the RIETI (Research Institute of Economy, Trade and Industry, See Nagaoka and Walsh (2009) for details of the survey design). The survey covers the patents by Japanese applicants who applied for Japanese patents with priority years between 1995 and 2001. A majority of survey questionnaires (around 70%) were sent to the randomly selected triadic patents which were not only granted patents in the United States, and but also were applied for in Europe and Japan. They are of higher quality than the average. Oversampling high-quality patents helps us avoiding sending most questionnaires to those with relatively low quality patents. RIETI received 3,658 responses on triadic patents and 1,501 responses on non-triadic patents, the population of which were also randomly selected. We focus only on those patents applied by a single applicant, with an inventor belonging to firms. The survey provides us with the characteristics of the R&D projects that yielded these patents as well as the patent and inventor information. We supplemented the dataset with the business information (e.g. sales size, R&D) of the applicant firms from the Basic Survey of Business Activities (BSBA) of the Ministry of Economy, Trade and Industry (METI) as well as the US patent information obtained from the NBER patent database. We cover the R&D projects of around 400 matched firms.

We would like to begin looking at the composition of projects by business objectives. We identify 4 business objectives. The survey asks “What is the objective of the R&D project that led to the development of this patent?” As shown in Figure 1, 50% of the projects (*core business projects*, hereafter) target the core business of the firm. 22% of the projects aim at creating new business line and 8% at enhancing the technology base of the firm or cultivating new seeds. Figure 2 shows the stage and scope of R&D projects. We identify 9 types of projects: 7 types of projects in R&D stage and 2 types of projects in non-R&D stage (technical service such as design and engineering or the other stage). Pure projects, covering only one of basic, applied or development stage, account for roughly 75% of the projects. Pure development project is the most common and accounts for a half of the projects. 19 % of the all projects involve basic research (8% of them are pure basic research projects and 11 % are the projects covering basic research and the other stage). 6% of the projects are integrated: covering all three stages from basic research to development. The projects from non-R&D stage account for 10% of the projects in each business objective. Technical service is as frequent as basic research.

(Figure 1, 2)

Figure 3 show how frequently the various knowledge sources are recognized as very important for suggesting the R&D project which yielded the focal invention. It identifies the most important 9 sources: patent literature, vertical source (the max of the score of the importance of the users and that of the suppliers), internal source (excluding co-inventors), scientific literature, competitors, fairs or exhibitions, technical conferences and workshops, research organization (the max of the score of the importance of a university and that of a public laboratory) and standards documents. According to Figure 3, patent literature and vertical source are recognized to be very important for more than 20% of the projects. Scientific literature and internal source follow (they are very important for more than 15% of the projects). The fact that internal knowledge source is very important most frequently does not imply that the invention which depends most on it has a high value. We will see later from our econometric investigation that the project for which internal knowledge source is very important does not have a good performance.

(Figures 3)

There are two major measures of inventive efforts: the number of inventors of the focal patent and the total man months spent by all researcher for the project (we have 8 ranks: 1-3, 4-6,7-12,13-24,25-48,49-72,73-96, 97 or more). It is important to note that the number of inventors is one component of the total man months. As shown in Figure 4, two thirds of the projects involve 2 or more 2 inventors and around one fifth of the projects involve 4 or more inventors. As shown in Figure 5, one quarter of the projects involve only up to 3 man months, and another one quarter of the projects involve more than 25 man months. Thus, there exist large variations of man months spent for the project.

(Figure 4,5)

There are two performance measures of R&D activity we focus in this paper. One is the number of patents generated from the R&D project (variable name *size_pat*). The survey asks “How many domestic patents do you expect your organization will be granted from the R&D project that led to the discovery of this patent?” The respondent chooses from 1 (one. only this patent), 2 (two to five), 3(six to ten), 4 (eleven to fifty), 5 (fifty one to one hundred), 6 (more than one hundred). The other performance measure is the value of the patent (variable name *valued2*), which is the answer to the following question: "How would you rank the economic value of the surveyed patent among the technological accomplishments in the same technological area during the same period in Japan?" Again, it is a multiple-choice question with the choices: 1 (Unknown: treated as missing in *valued2*), 2 (below 50 percentile), 3 (above 50th percentile), 4 (top 25th percentile), 5 (top 10th percentile). Note that it is a relative performance measure. Figure 6 and Figure 7 show the distributions of these two performance measures. According to Figure 6, 70% of the projects generate less than 5 domestic patents from the project, while 4 % of the projects produce more than 50 patents. According to Figure 7, 9% of the sampled patents belong to top 10% rank.

(Figure 6,7)

4. Empirical Models

First, we estimate knowledge production function (Griliches (1984)), corresponding to equation (3) and (5) in section 2. Compared to the standard formulation, we specify the project characteristics in detail. We use the number of patents granted for the inventions from the project (*size_pat*) and the value of the sampled patent (*valued2*). The econometric model we use is the following form of the ordered logit model:

$$y^{*}_{jft} = K_{ft}\beta + Z_{j}\delta + (dummies) + \varepsilon_{jfi} \qquad (14)$$

where y^{*}_{jft} is the latent variable for the number of patents (*size_pat*) and for the inventor's self-evaluated economic value of the focal patent (*valued2*) from project j in firm f in application year t, K_{ft} is the firm f's characteristics in year t, and Z_j is the project j's characteristics (including the efforts or R&D input variables for the project). We present a result using the dummy for the internal use of a patent (*use2*) as a dependent variable replacing the above subjective value in Appendix Table 2 for two reasons. A specification based on the use is more robust to missing variable of inventor efforts (see section 5.1 for details). Second, whether the focal patent is internally used either for the product of a firm or for its production process could be more objectively decided. The dummies include the application year dummies (1995-2002), and 38 technology class dummies as controls. $\varepsilon_{j,i}$ is the error term. We take into account the potential correlation of the error terms across the projects of a firm by clustering.

Since effort variables (a part of Z_j), especially man months, are likely to be endogenous to missing variables such as firm or project specific market or technological opportunity, the coefficients of these variables would likely to be upward biased and the contribution of the other variables on productivity would be underestimated. In order to assess the importance of such bias, we also estimate a “reduced model”, which excludes input or effort variables from project *j*’s characteristics variables.

Second, we estimate the equations giving the knowledge inflow and the firm’s choice of the inventive efforts, which corresponds to equations (1) and (12) in section 2. In order to evaluate the direct and indirect effects of firm characteristics, we do not include the knowledge flow variables for equation (12) by using equation (1). The basic structure of the equation for estimation is the same as equation (14), except for that project *j*’s characteristics do not include the information inflow from knowledge sources nor inventive efforts. The dependent variables are the importance of knowledge inflows to the conception of the research project for 5 sources (*cncpt_own* for internal knowledge, *cncpt_sci* for scientific literature, *cncpt_pat* for patent literature, *cncpt_v* for vertical partner (suppliers or users) and *cncpt_res* for research base such as a university), the number of inventors (*lninventors*) and the total man months for research both in the natural logarithm (*lnmonth2*). The importance of knowledge inflows are measured by Likert scale (0 for “non-use”, 5 for “very important”). We also introduce the indicator for a PhD of the inventor as a control over human capital input. Since there is a possibility that the level of knowledge inflow for suggesting a project depends on the size of inventor team (that is, the team of inventors search for useful idea before actually initiating the research project), we also estimate the equation with additional controls over the size of the number of inventors of the focal patent and the education level of the inventor, which is provided in the appendix Table 3.

The independent variables for project characteristics include business objectives (core business (base), non-core business, unclassified existing business, new business, enhancing technology base, and others), research stage (basic research, applied research(base), or development), and type of research project (new product, new process(base), improvement of product, or improvement of process). Knowledge source variables are also used as independent variables for some specifications. Table 1 provides descriptive statistics.

(Table 1)

As for firm characteristics, variable *lnsales* indicates the logarithmic sales of the applicant firm, the variable *rds* indicates the R&D intensity of the firm (R&D/sales). We have chosen the R&D intensity of the firm instead of more symmetric logarithm form (ln1rds=*ln (R&D+1)/Sales*)[4], due to the former better explanatory power of the value of the patent. But the main results are not dependent on this choice (see Appendix Table 1, in particular Model 2). We also use the US patent stocks of each firm in each technology class relevant to the focal patent (*ln1uspat=ln(1+us patent stocks for each sector)*), which is constructed from the NBER patent database, using the perpetual inventory method with depreciation rate of 15%. Since only a half of the Japanese patent applications are examined while the Japanese firms have to pay additional fees and cost of translations for filing US patent applications so that these are screened, the US patents by the Japanese firm are more likely to be good indicators of knowledge production of the Japanese firms. The coefficient of *lnsales* measures the effect of firm size, including that of complementary assets, not captured by the patent stock variable.

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[4] We add 1 million yen (around 10,000 dollars) to R&D expenditure, since some firms report zero values.

The size of sales reflects both the physical complementary assets such as production as well as non-physical complementary assets such as the strength of brand names of the firm[5]. The R&D intensity at the firm level measures the R&D capability of a firm as well as potential spillover from concurrent R&D within the firm. If there is a strong economy of scale or scope at firm level in R&D, firm size measure as well as R&D intensity would have a positive effect on R&D productivity at project level.

Technology class dummies and application years (adjusted for priority years) of the patents control for the variations of technological or demand opportunities across sectors and over time. We also use the calendar time between the initiation of research and the application of the focal patent *(res_app*) and the triadic patent dummy as additional controls. It is more likely that the invention process will produce more inventions if more calendar time is consumed between the initial of the project to the application of the focal patent even for given number of man months and that of inventors. We expect that the sub sample of triadic patents have higher means than those of non-triadic patents in R&D performance measures.

5. Estimation results

5.1 Findings from knowledge production function

Table 2_A shows the results for R&D productivity with the number of patents (*size_pat*) as a dependent variable[6]. Model 1 and 2 provides gross outputs without controlling knowledge inflow and effort variables, while Model 3 provides outputs with controlling knowledge inflow variables, and Model 4 provides outputs with further controls over inventive efforts. Model 1 does not have the patent stock variable and covers non-listed firms too so that it cover 3,400 projects from more than 700 firms, while Model 2 has the patent stock variable

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[5] The size of (tangible) assets is found to be less significant than the size of sales.

[6] In order to examine whether focusing on relatively more valuable patents would make any difference in the results, we also did the estimation restricting our sample to triadic patents in addition to the one with the total sample. We generally see the same results for the two samples.

and covers only listed firms (2,700 projects from 440 firms). Overall the coefficients of the common variables of these two Models are similar. In addition, the coefficients of Model 3 and Model 4 are also very similar, implying that the endogeneity of inventive efforts does not significantly affect the coefficients of the rest of the variables, including firm characteristics.

We will begin with briefly discussing the results of the estimations for objectives and stages of the research project. A project targeting new business generates most patents from a project. According to the estimates, it amounts to around 20% more. We will later see that the value of a patent from such project tends to be low (see Table 2_B). The combination of these two evidences seems to indicate the importance of patenting in new business, for which patenting plays a relatively important role for appropriation. Compared to pure applied research, the integrated project generates significantly more patents (40% more), even controlling for the research input such as man hours and the number of inventors. A similar pattern can be observed for that combining applied research and development. On the other hand, pure development project produces the least number of patents. The improvement projects (especially for process improvement) generate significantly smaller number of patents, although such difference declines once we control for inventive inputs.

(Table 2_A)

The significance of knowledge inflow to getting an idea for a research project varies significantly across sources, according to Model 3 and 4. Patent literature for the conception of inventions is significant for the number of patents from a project. Use of scientific literature has a significantly positive effect on the number of patents only if we do not control for inventive efforts. The use of the knowledge from university and a research laboratory has a highly significant effect on the number of patents (at 1% statistical significance). While neither internal source nor vertical knowledge source is significant, it does not mean that they are not useful for inventions. What estimations suggest is that the research projects using these knowledge sources more significantly does not produce more patents, even though they still provide opportunities for inventions.

According to Model 4, the (total) man-month of researchers is positively and highly significantly associated with the number of patents generated from the project. The implied elasticity is 0.2, which is very similar to the level found by Henderson and Cockburn (1996) for the number of patents from drug discovery, suggesting a significant decreasing return to the project level R&D effort. In contrast, the number of inventors variable is not significant, implying that there is no additional effect of the team size (note that team size is a part of total man months). A PhD is also significant for the number of patents (the effect amount to around 15%). We have to bear in mind that these inventive efforts variables are likely to be overestimated, due to project-level missing variables such as those on technological or market opportunities, although we extensively control for the project characteristics and technology sectors.

There are three firm level variables: *sales, R&D intensity and patent stock.* Firm scale matters since the sum of the coefficients of *lnsales* and *ln1uspat* is highly significant. As shown in the last line of Table 2_A, it is positive and highly significant. The implied elasticity is around 0.06, which is significantly lower than those (around 0.25) estimated by Henderson and Cockburn (1996) for the effect of firm level R&D on the number of drug discovery patents (triadic patents). Very importantly, among three firm level variables (sales, R&D and patent stock), only sales variable is highly significant. If we replace the sales variable by the R&D variable and drops the R&D intensity, the R&D variable becomes significant, as shown in Appendix Table 1 (see Model 1). Once we have sales variable, a firm level R&D or patent stock is not significant (see Model 2 and 3 in Table 2_A and Model 2 in Appendix Table 1), while a project level R&D effort is highly significant. This strongly suggests that the source of scale economy is not internal knowledge inflow to the project. It is more likely to be appropriation advantage due to complementary assets or the firm level capability to absorb external knowledge. Appendix Table 1 also shows that the main results are not dependent on the choice of the R&D intensity.

We then turn to the value of the focal patent as the output measure of R&D. According to Table 2_B, a project for non-core business produces a significantly less valuable patent[7]. Among stages of research, the integrated project tends to generate a most valuable patent, even controlling for the research input such as man hours and the number of inventors (40% more). We observe a similar result for the number of patents (see Table 2_A). These results may reflect a selection (integration is chosen to gain a speed in implementing a project with a high expected return) or an efficient transfer of knowledge across stages of research in an integrated project. An improvement projects generate significantly less valuable patents, although such difference declines once we control for inventive inputs.

(Table 2_B)

According to Model 7 and 8, the significance of knowledge inflow to getting an idea for an invention varies significantly across sources. Similar to the effect on the number of patents, the use of the knowledge from university and a research laboratory has a significant and positive effect on the value of a patent. This may indicate higher private value of pre-publication research outcomes at university and the other public research organization. Vertical knowledge source is also significant and positive, indicating the importance of combining knowledge such as those of technology and market across organizational boundaries (note that we did not observe no negative return on the number of patents). Very interestingly, internal knowledge source has a significantly negative coefficient[8]. Later we show that the main source of internal knowledge is closely related with the firm's patent stock

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[7] Assuming log normal distribution of the value of the patent, the implied effect is around 20% less.

[8] Assuming log normal distribution of the value of the patent, the implied effect (the patent from a project very importantly driven by internal knowledge source has value of around 25% smaller.

(See Table 3). Own patented technologies may not provide (privately) valuable knowledge for a research project, because they are publicly known. Patent literature and scientific literature are not significant, perhaps again due to their public nature.

Both the (total) man-months of researchers and the inventor team size are positive and highly significant. The increase of man month per an inventor, not accompanied with the increase of inventor, has the effect amounting to less than one half of the effect of the increase of inventor team size (the coefficient size is 0.14 vs. 0.34)[9]. This implies that inventor team size has a significant additional effect on the value of a patent, controlling for the total man months, while it is not for the number of patents. A PhD is significant only at 10 % level of statistical significance. Appendix Table 1 provides results consistent with the above finding. Inventor team size has a significant additional effect on the value of a patent, controlling for the total man months.

Firm scale does not matter for the value of the focal patent since the sum of the coefficients of *lnsales* and *ln1uspat* is insignificant (both are insignificant), as shown in the last line of the Table 2_B. There is no significantly negative effect of the sales size on the value of the focal patent, as would be implied by Hypothesis 1 on complementary assets. There are two explanations for accounting for this gap. First, our specification may not fully control the endogenous increase of inventive efforts in response to the increase of complementary assets. As discussed in section 2, such increase would enhance the qualities of infra-marginal high-quality inventions. The probability of the use of the inventions is less subject to such effect, since most of these high quality inventions are already used and most of low quality inventions will remain unused even if there is a marginal increase of inventive efforts. In fact, as shown in Appendix Table 2, the sales size has a significantly negative effect on the use of the focal invention. Second, there may be firm scale advantage due to more inflow from

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[9] Assuming log normal distribution of the value of the patent, the implied elasticity for the increase of man months per inventor is 0.05 and that of the inventor team size if 0.11.

external knowledge sources. We will see in next section that an inventor in a large firm recognized high importance on knowledge inflow from scientific literature.

On the other hand, R&D intensity of a firm has a positive and significant coefficient. One potential interpretation of such effect might be spillover from concurrent R&D. However, if it is important, it should also matter for the number of patents, but it is not (see Table 2_A). In addition, R&D intensity is not positively correlated with the level of the importance of internal knowledge inflow, once we control for the patent stock (See Table 3). A more natural interpretation is the capability of a firm to systematically produce high value patents, including the cases where a firm “owns” a number of very productive R&D opportunities. In such case, a firm not only generates valuable patents (a patent which yields large cost reduction or large increase of the willingness to pay) but also spends a high level of R&D so that its R&D intensity becomes high (Dasgupta and Stiglitz (1980)).

5.2 Findings from knowledge inflow

Table 3 shows how the knowledge inflows from five major sources are affected by project and firm characteristics. As shown in the last line of Table 3, firm level scale economy exists for internal knowledge source and for scientific literature. Thus, a project in a lager firm has more internal knowledge inflow and that from scientific literature, showing the existence of scale economy. Such enhanced inflows would result in more number of research projects initiated from a firm. Scale effect does not exist for patent literature and for university and research institutes.

(Table 3)

Table 3 also provides information on for which type of a project each knowledge inflow is important and on the sources of the scale effects. Internal knowledge source is less important for an R&D project targeted to new business and more important for a project involving applied and development. As for the effects of firm characteristics, internal knowledge inflow is significantly and positively affected by the patent stock of the firm in the technology sector of the focal patent. That is, internal knowledge inflow is significantly affected by the past inventive activities of the firm. Neither the current R&D nor the sales level of a firm is significant. As for scientific literature, it is important when the project covers basic research. It is not affected by the patent stock (it actually has a negative coefficient), nor by the level of R&D of the firm but by the sales size of a firm. This seems to indicate that a large firm is more likely to engage in basic research due to its appropriation advantage.

Knowledge inflow from patent literature is not strongly dependent on the project characteristics. It is also independent of firm size. This may not be surprising, since such literature is publicly disclosed and inventors in both large and small firms regularly review such literature to evaluate their research project and the patentability of its output. Knowledge inflow from vertical partners (suppliers and user) is particularly important for a research at the stage of technical service (post R&D stage). Its importance declines significantly with firm size (declines both with sales and with patent stock). It also declines with the level of R&D. These results seem to suggest that the division of inventive tasks is differently organized for a large firm and for a small firm. A small firm outsources the seeds of the inventions to users and suppliers, while a large firm develops them based on its own effort. Finally, knowledge inflow from a university and a research institution is important for a project involving basic research and for a project targeted at new business. While it is not size dependent, it is significantly less important in the technology area where the firm has a large patent stock. This indicates that a firm looks for collaboration with a university in those sectors where it has a weak technology position (note that we control for technology class).

Table 2 in the appendix shows the estimation results with additional controls of the number of inventors and the education level of the inventor but the results are very similar.

One important additional result is that the size of inventor team is significantly positive for all sources of knowledge. This seems to indicate that a larger team enables a team to collect information more intensively from diversified sources. In addition, a PhD inventor facilitates the use of information from scientific and patent literature as well as from the research base.

5.3 Inventor team size and man months

Table 4 shows how the size of inventor team and the size of man months are related to the project and firm characteristics. The team size is small when the project focuses on the development stage. The size of man months is small when the project is improvement and the length of the research duration up to the patent application is short. The projects for strengthening technology base tend to require significantly less of the two. Both are positively dependent on firm size. In particular, the number of inventors increases significantly with sales size while it decline with the size of patent stock. The elasticity is 0.04 and 0.03, which implies that a number of inventors expand much more rapidly than the man months per inventor, as firm size increases. Furthermore, we have found earlier that the size of inventor team matters for the value of an invention, even if we control for total man months. Thus, inventor team size is also an important source of scale economy of a large firm.

(Table 4)

In order to probe the sources of scale effect on inventor team, Model 3 and model 6 in Table 4 introduce the Herfindahl index based on the sector shares of the US patents of each firm and its debt asset ratio. The Herfindahl index measures (negatively) the diversity of the technological skills of the inventors of a firm. Debt asset ratio measures the financial constraint of a firm. The coefficients for Model 3 show that the technological diversity of a firm helps a firm to expand the size of the inventor team, while debt asset ratio does not. In addition, neither the technological diversity nor the debt asset ratio of a firm not significantly affects man months. According to Model 6, these results suggest one source of the scale economy of a firm is the technological diversity of a large firm.

6. Conclusions and discussions

This paper has explored the sources of firm level scale economies in R&D, based on the unique project level data from a new large-scale survey of Japanese inventors, matched with firm level data. Our data covers more than 400 firms and around 2500 patents and incorporates very detailed project level information. We have focused on four potential sources: complementary assets, internal and external knowledge inflows and inventor team size. Major findings are the following. A larger firm tends to generate more patents from a research project but no more valuable patent, controlling for the objectives and the inventive efforts for the project, showing the existence of firm scale economy. The sales size of a firm rather than its R&D (or patent stocks) significantly affects the number of patents from the project. While the firm level R&D significantly explains the number of patents from the project, controlling for project level R&D (inventor man months), it becomes insignificant once we have sales variable. Moreover, the focal patent becomes less used as firm size increases. These results strongly suggest that the main source of such scale economy is not internal knowledge inflow within a firm but its appropriation advantage. This finding is further reinforced by our finding that internal knowledge inflow to the conception of the project does not contribute to high R&D performance.

An inventor in a large firm often gets important information from internal knowledge inflow as well as from scientific literature. Internal knowledge inflow is significantly and positively affected by the patent stock of the firm in the technology sector of the focal patent, while scientific literature is significantly and positively associated with the sales size of a firm. However, the performance of an R&D for which internal knowledge is important tends to be low.

The size of an inventor team increases with the firm size and its technological diversity. On the other hand its debt asset ratio does not constrain the team size. A larger team size is significantly associated with higher patent value, while it has no effect on the number of patents, controlling for total man months. Thus, inventor team size is an important source for firm level scale advantage.

Some notable the other findings are the following.

(1)A project targeting new business generates most patents among those for core-business, non-core business, new business and technology base (or seeds). However, the value of a patent from such project tends to be low. This seems to indicate the importance of patenting in new business, for which patenting plays a relatively important role for appropriation.

(2)Integrated project covering all three stages of research and development shows a good performance in both the number of patent and the value of the focal patent. This may reflect a selection (integration is chosen to gain a speed in implementing a project with a high expected return) or an efficient transfer of knowledge across stages of research in an integrated project.

(3) The research project driven by university and the other public research in its conception performs better than the research driven by scientific and technical literature. This may indicate higher *private* value of pre-publication research outcomes at university and the other public research organization.

(4) The knowledge inflow from users or suppliers helps a firm to generate a high value patent, indicating the importance of combining knowledge (such as those of technology and market) across organizational boundaries. However, they are important at development stage, so that they do not substitute for scientific discoveries and knowledge.

(5)R&D intensity of a firm (rather than the scale of R&D) significantly accounts for the value of a focal patent, controlling for project level R&D and the other firm level variables (sales and patent stocks). The capability to identify high return R&D projects seems to be more important than the scale of R&D.

One source of a potential bias of our study is our patent based selection of the projects for our survey. In particular, a small firm may selectively patent its inventions than a large firm so that our survey might have picked relatively high performance R&D projects for a small firm. This sample selection, however, works against us finding the scale economy of a firm in knowledge production function. Thus, our conclusions are robust to this potential bias. Similarly, although we cannot control the endogeneity of project-level inventive efforts such as man-months, it tends to work against finding the significance of firm level scale advantage.

One caveat we would like to make is that there can be significant differences across technology sectors in the importance and the sources of scale economies at firm level. Our preliminary investigations suggest that scale economy is more important in chemical and computer technologies, but it is less so in mechanical technology. In computer technology, the size of firm sales is much more important than its patent stock as a source of scale economy while they are similarly important in chemical technology. We intend to conduct more detailed analysis of the variations and its causes across sector differences. For an example, internal knowledge flow may be more important in the sectors where knowhow is important and technology development is cumulative. Our results in this paper provide an “average” picture, which depends on the sectoral composition of the Japanese industry.

We can draw the following implications. First, internal knowledge stock often does not confer strong source of competitive advantage. The performance of an R&D for which internal knowledge is important tends to be low, although such knowledge is still useful for generating R&D projects. One reason would be that much of such knowledge is often publicly known (certainly so for patented technologies). Another reason might be a diminishing return for exploiting internal knowledge. Going beyond the organizational border for “new combination" for invention seems to be important.

Second, it would be important to have a team of inventors with efficient scale and diversity, taking advantage of the internal inventor resources of a firm. Our research suggests the possibility that one important source of scale economy is the capability of a large firm to form a large scale team, which can combine different technical expertise. Internal knowledge inflow may not automatically occur, even if there is a good reservoir of knowledge inside a firm. Such knowledge could be activated only if the inventor embodying such knowledge joins in the team and works together.

Third, while our research suggests that the research project driven by university and the other public research in its conception performs better than the research driven by scientific and technical literature. This result does not indicate low social value of the scientific publication, since its social value is significantly not reflected in private value, due to research competition and spillover. It is important to note that scientific publication is more often used as a source of inventions than the direct contacts with university and the other public research organizations (see Figure 3).

While an integrated project covering all three stages of research and development shows a good performance in both the number of patent and the value of the focal patent, there is some evidence that a large firm is less likely to engage in such project. One possibility causing such correlation is more specializations of a large firm between research and development and the existence of organizational barriers for an integrated project in such firm. This may be an interesting future research topic.

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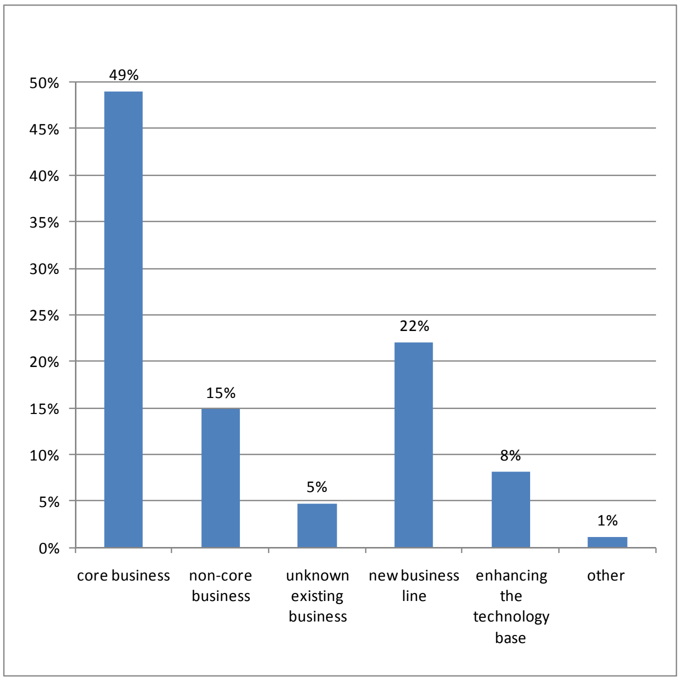
Figure 1 Composition of projects by business objective (triadic and non-triadic inventions)



Note. Around 3,100 triadic patents and 1,300 non-triadic patents

Figure 2. Stage and scope of R&D projects (triadic and non-triadic inventions)

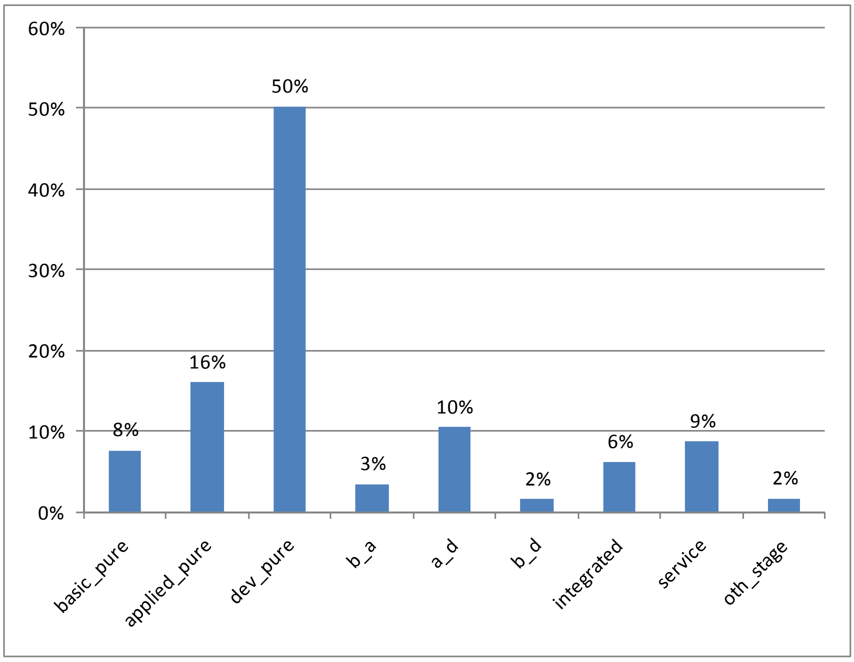


Figure 3. Knowledge source for getting an idea for R&D projects (very important, %, triadic

and non-triadic inventions)

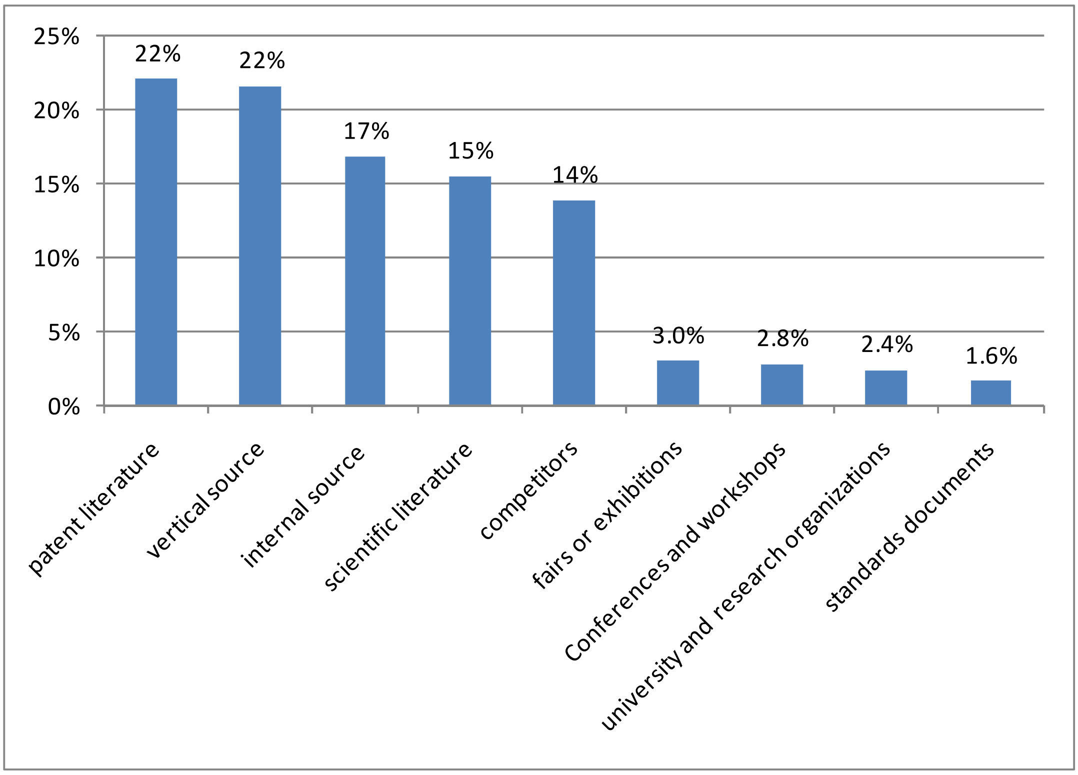


Figure 4. Distribution of the number of inventors of the focal patent (triadic and non-triadic inventions)

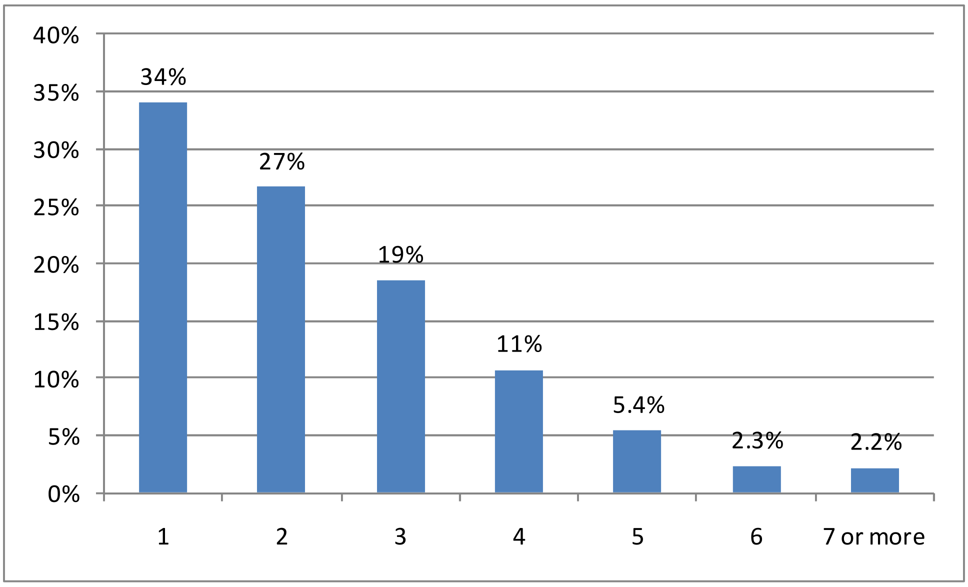


Figure 5. Distribution of the man months of researchers for a project (triadic and non-triadic inventions)

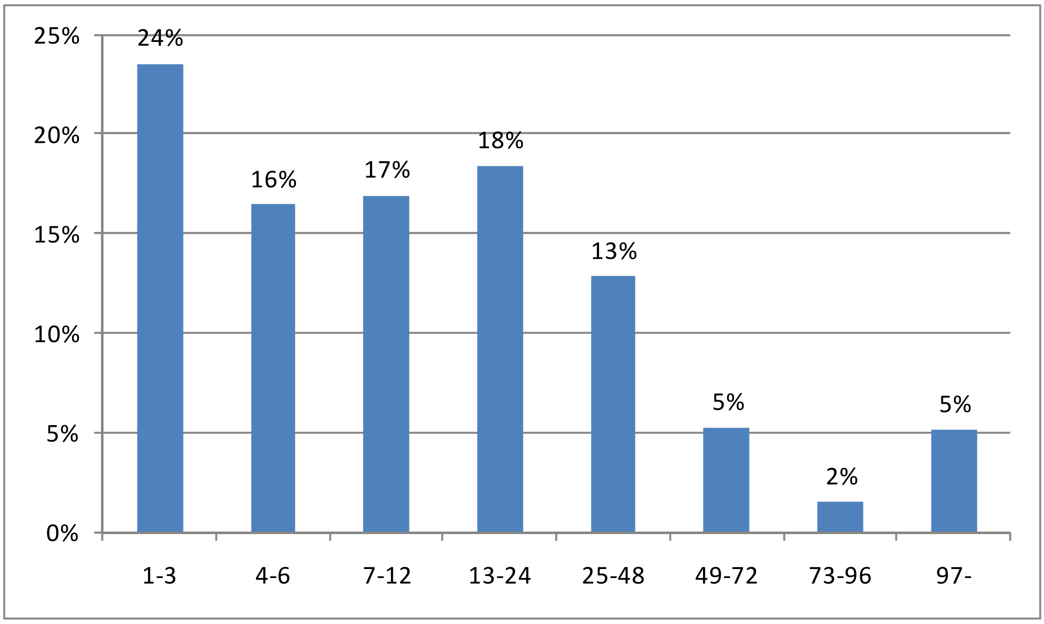


Figure 6. Distribution of the number of domestic patents from a project (triadic and non-triadic inventions)

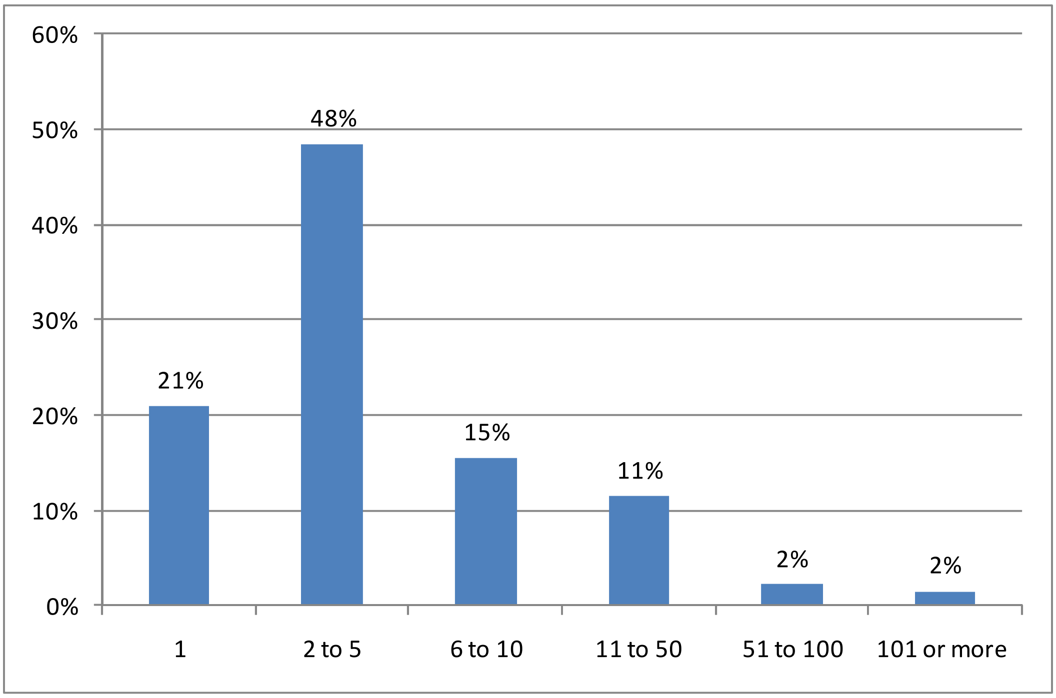


Figure 7. Distribution of the value of a patent from the project (triadic and non-triadic inventions)

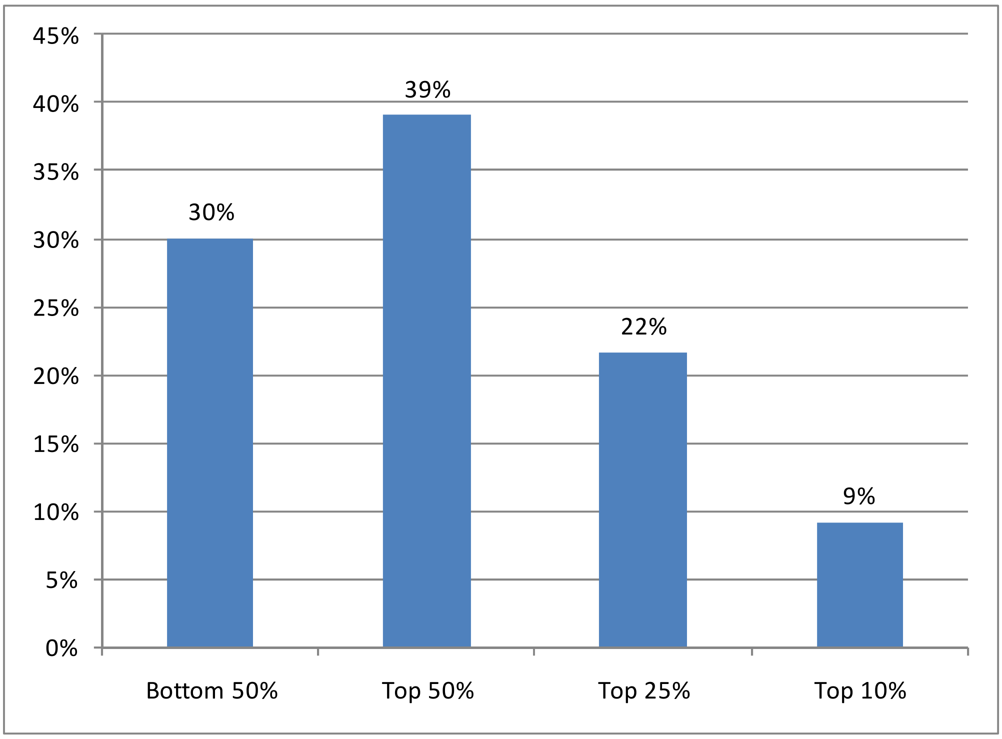


Table 1. Descriptive statistics

Variable	Explanation	Obs	Mean	Std. Dev.	Min	Max
size_pat	the number of patents fom the patent	3,460	2.324	1.086	1	6
valued2	economic value of the focal patent	2,491	3.081	0.921	2	5
use2	use of the focal patent by the applicant	3,452	0.515	0.500	0	1
cncpt_sci	scientific and technical literature	3,432	2.961	1.744	0	5
cncpt_pat	patent literature	3,441	3.314	1.636	0	5
cncpt_own	internal knowledge	3,412	3.334	1.483	0	5
cncpt_v	vertical partner	3,431	3.043	1.816	0	5
cncpt_res	research base such as a university	3,409	1.509	1.595	0	5
objective3	Business objective of research					
2	non-core business	3,504	0.152	0.359	0	1
3	unclassified existing business	3,504	0.045	0.207	0	1
4	new business	3,504	0.224	0.417	0	1
5	enhancing technology base	3,504	0.079	0.270	0	1
6	other	3,504	0.007	0.086	0	1
basic_pure	pure basic	3,504	0.071	0.257	0	1
dev_pure	pure development	3,504	0.504	0.500	0	1
b_a	basic&applied	3,504	0.036	0.186	0	1
a_d	applied&dev	3,504	0.111	0.314	0	1
b_d	basic&applied	3,504	0.015	0.123	0	1
integrated	integrated	3,504	0.063	0.243	0	1
service	technical service	3,504	0.086	0.281	0	1
oth_stage	oth_stage	3,504	0.014	0.116	0	1
prodproc	type of research project					
2	improvement of process	3,504	0.086	0.280	0	1
3	new product	3,504	0.601	0.490	0	1
4	improvement of process	3,504	0.218	0.413	0	1
5	other	3,504	0.011	0.105	0	1
lnsales	logarithm of sales of a firm	3,504	12.710	1.788	6.757	16.024
rds	R&D intensity (R&D/sales)	3,504	0.053	0.038	0.0	0.629
uspatent_stock	stock of us patents in the technology secto	2,832	137	248	0.0	2018
ln1uspat	logarithm (1+uspatent_stock)	2,832	3.516	1.888	0.0	7.611
hhi_pat	Herfindahl index of the patents granted	2,832	0.202	0.144	0.1	1
debtasset	debt asset ratio	3,504	0.450	0.280	0.000	2.492
res_app	time between initiation of the project to the application of the focal patent	3,408	1.702	1.503	0.080	15
triadic	dummy for a triadic patent	3,504	0.704	0.457	0	1
applyear	application year	3,504	1,997.953	1.848	1,995	2,002
inventors	the number of inventors	3,504	2.489	1.631	1	21
month2	the total man months for research	3,457	23.184	33.747	1.5	143
phd	A dummy for a PhD	3,484	0.085	0.279	0	1

Table 2_A　Determinants of R&D Performance at project level (the number of patents granted) (Clustering on applicant, single applicant only)

			R&D Productivity (1): the number of patents from the project (size_pat)											
			Model 1			Model 2			Model 3			Model 4		
			Number of obs = 3380			Number of obs = 2730			Number of obs =2649			Number of obs = 2629		
			711 Clusters			436 Clusters			434 Clusters			432 Clusters		
			Log pseudolikelihood = −4345.9807 Pseudo R2 =			Log pseudolikelihood = −3570.9909 Pseudo			Log pseudolikelihood = −3426.9093 Pseudo			Log pseudolikelihood = −3313.6094 Pseudo		
				Robust			Robust			Robust			Robust	
		Variable	Coef.	Std. Err.		Coef.	Std. Err.		Coef.	Std. Err.		Coef.	Std. Err.	
Business Objective of R&D (Base:core)	Non-core	_Iobjectiv~2	−0.136	0.093		−0.158	0.107		−0.103	0.108		−0.138	0.112	
	Unknown	_Iobjectiv~3	−0.289	0.162	*	−0.106	0.189		−0.036	0.182		−0.008	0.174	
	New business	_Iobjectiv~4	0.314	0.098	***	0.350	0.117	***	0.320	0.128	**	0.327	0.128	**
	Technology base	_Iobjectiv~5	0.002	0.171		−0.001	0.207		0.022	0.200		0.085	0.204	
	Other	_Iobjectiv~6	1.038	0.699		0.621	0.677		0.796	0.600		0.587	0.604	
Scope and stage of research (base: applied)	basic	basic_pure	0.076	0.147		0.057	0.157		−0.060	0.160		−0.061	0.161	
	dev	dev_pure	−0.149	0.124		−0.266	0.128	**	−0.295	0.125	**	−0.248	0.121	**
	basic&applied	b_a	0.169	0.170		0.134	0.181		−0.002	0.189		−0.015	0.188	
	applied&dev	a_d	0.343	0.131	***	0.294	0.147	**	0.236	0.148		0.176	0.148	
	basic&applied	b_d	0.339	0.239		0.305	0.279		0.331	0.281		0.400	0.291	
	integrated	integrated	0.689	0.176	***	0.614	0.205	***	0.487	0.211	**	0.504	0.203	**
	service	service	−0.186	0.121		−0.244	0.148	*	−0.182	0.153		−0.103	0.147	
	oth_stage	oth_stage	0.147	0.291		0.318	0.349		0.383	0.363		0.378	0.347	
Technological Objective of R&D (base:new process	Process improvement	_Iprodproc_2	−0.670	0.182	***	−0.599	0.199	***	−0.612	0.203	***	−0.450	0.210	**
	New product	_Iprodproc_3	−0.031	0.140		0.093	0.152		0.103	0.159		0.083	0.171	
	Product improvement	_Iprodproc_4	−0.430	0.144	***	−0.355	0.155	**	−0.329	0.158	**	−0.228	0.163	
	Other	_Iprodproc_5	−0.607	0.366	*	−0.545	0.438		−0.365	0.441		−0.255	0.477	
Knowledge source for conception	patent literature	cncpt_pat							0.072	0.033	**	0.052	0.031	*
	scientific literature	cncpt_sci							0.063	0.033	*	0.038	0.031	
	internal	cncpt_own							0.026	0.028		0.010	0.029	
	vertical	cncpt_v							0.014	0.024		0.015	0.024	
	research base	cncpt_res							0.070	0.027	**	0.081	0.028	***
Inventors input	number of inventors	lninventors										−0.039	0.074	
	man month	lnmonth2										0.417	0.041	***
	PhD	PhD										0.321	0.117	***
Firm characteristics	Sales	lnsales	0.177	0.027	***	0.144	0.043	***	0.107	0.048	**	0.103	0.053	*
	RD/sales	rdsales	−0.248	0.839		−0.057	0.912		0.201	0.926		0.680	0.991	
	Patent stock	ln1uspat				0.017	0.026		0.044	0.028		0.041	0.028	
control	research length	lnres_app	0.427	0.045	***	0.446	0.052	***	0.401	0.052	***	0.145	0.052	***
	triadic patent	triadic	0.264	0.076	***	0.195	0.085	**	0.207	0.086	**	0.118	0.090	
Firm scale effect	Firm size	lnsales+ln1usp	0.177	0.027	***	0.161	0.037	***	0.152	0.039	***	0.144	0.043	***
	Note. * significant at 10%, ** significant at 5%, *** significant at 1%.　Cutoff points, dummies for application years and for US technology classes are not reported.													

Table 2_B　Determinants of R&D Performance at project level (the economic value of the patent)　(Clustering on applicant, single applicant only)

	R&D Productivity (2): the value of a patent from the project (valued2)											
	Model 5			Model 6			Model 7			Model 8		
	Number of obs = 2437			Number of obs = 2011			Number of obs = 1946			Number of obs = 1933		
	578 Clusters			385 Clusters			382 Clusters			380 Clusters		
	Log pseudolikelihood = −2964.1256 Pseudo			Log pseudolikelihood = −2459.3033 Pseudo			Log pseudolikelihood = −2373.1149 Pseudo			Log pseudolikelihood = −2343.9992 Pseudo		
		Robust			Robust			Robust			Robust	
	Coef.	Std. Err.		Coef.	Std. Err.		Coef.	Std. Err.		Coef.	Std. Err.	
Non-core	−0.503	0.121	***	−0.501	0.132	***	−0.541	0.137	***	−0.523	0.137	***
Unknown	0.000	0.213		0.129	0.229		0.146	0.228		0.175	0.230	
New business	−0.165	0.095	*	−0.140	0.107		−0.149	0.112		−0.183	0.109	*
Technology base	−0.203	0.168		−0.320	0.177	*	−0.325	0.178	*	−0.295	0.187	
Other	0.083	0.344		−0.111	0.542		−0.148	0.553		−0.207	0.551	
basic	−0.110	0.154		−0.162	0.173		−0.115	0.180		−0.120	0.180	
dev	−0.035	0.115		−0.107	0.130		−0.067	0.132		−0.002	0.135	
basic&applied	0.442	0.211	**	0.372	0.228		0.392	0.237	*	0.395	0.237	*
applied&dev	0.264	0.136	*	0.206	0.146		0.238	0.147		0.268	0.147	*
basic&applied	0.188	0.284		0.146	0.319		0.230	0.329		0.263	0.336	
integrated	0.531	0.188	***	0.405	0.221	*	0.403	0.223	*	0.445	0.218	**
service	0.027	0.146		0.011	0.168		−0.014	0.185		−0.003	0.188	
oth_stage	0.185	0.426		0.093	0.468		0.057	0.517		0.018	0.536	
Process improvement	−0.568	0.160	***	−0.572	0.179	***	−0.537	0.198	***	−0.502	0.200	**
New product	−0.103	0.138		−0.084	0.145		−0.073	0.156		−0.078	0.157	
Product improvement	−0.592	0.154	***	−0.546	0.167	***	−0.506	0.175	***	−0.482	0.179	***
Other	0.472	0.401		0.491	0.445		0.510	0.477		0.545	0.483	
patent literature							0.019	0.041		0.012	0.041	
scientific literature							−0.004	0.039		−0.019	0.040	
internal							−0.117	0.035	***	−0.125	0.036	***
vertical							0.059	0.029	**	0.062	0.029	**
research base							0.078	0.032	**	0.082	0.032	**
number of inventors										0.205	0.066	***
man month										0.137	0.035	***
PhD										0.278	0.149	*
lnsales	−0.009	0.028		0.001	0.038		0.004	0.039		−0.013	0.038	
rdsales	2.412	1.089	**	2.306	1.106	**	2.211	1.112	**	2.166	1.091	**
Patent stock				0.010	0.032		0.018	0.033		0.020	0.034	
research length	0.264	0.059	***	0.273	0.066	***	0.243	0.067	***	0.133	0.068	*
triadic patent	0.572	0.093	***	0.516	0.106	***	0.492	0.106	***	0.456	0.105	***

Firm size	−0.009	0.028		0.012	0.034		0.022	0.035		0.008	0.032	

Note. * significant at 10%, ** significant at 5%, *** significant at 1%.　Cutoff points, dummies for application years and for US technology classes are not report

Table 3 Knowledge inflow for initiation of the project (Clustering on applicant, single applicant only)

			Ordered logit for cncpt_own			Ordered logit for cncpt_sci			Ordered logit for cncpt_pat			Ordered logit for cncpt_v			Ordered logit for cncpt_res		
			Number of obs = 2768			Number of obs = 2777			Number of obs = 2783			Number of obs = 2776			Number of obs = 2758		
			436 clusters			436 clusters			435 clusters			436 clusters			435 clusters		
			Log pseudolikelihood = −4041.8471 Pseudo R2 = 0.0133			Log pseudolikelihood = − 4080.7237 Pseudo R2			Log pseudolikelihood = −4076.0566 Pseudo R2 = 0.0190			Log pseudolikelihood = − 4187.2743 Pseudo R2 =			Log pseudolikelihood = −3982.1417 Pseudo R2 = 0.0293		
				Robust			Robust			Robust			Robust			Robust	
		Variable	Coef.	Std. Err.		Coef.	Std. Err.		Coef.	Std. Err.		Coef.	Std. Err.		Coef.	Std. Err.	
Business Objective of R&D (Base:core)	Non−core	_Iobjectiv~2	−0.152	0.106		−0.272	0.119	**	−0.207	0.114	*	−0.165	0.115		−0.284	0.110	***
	Unknown	_Iobjectiv~3	−0.174	0.174		−0.190	0.174		−0.477	0.155	***	−0.155	0.161		0.042	0.176	
	New business	_Iobjectiv~4	−0.238	0.092	***	0.152	0.098		0.045	0.089		−0.188	0.091	**	0.234	0.107	**
	Technology base	_Iobjectiv~5	−0.316	0.166	*	0.059	0.179		−0.168	0.171		−0.464	0.167	***	0.004	0.181	
	Other	_Iobjectiv~6	−1.093	0.774		−0.845	0.527		−0.727	0.592		−0.581	0.427		−0.421	0.613	
Scope and stage of research (base: applied)	basic	basic_pure	−0.043	0.154		0.311	0.141	**	0.234	0.147		−0.159	0.136		0.523	0.159	***
	dev	dev_pure	0.156	0.106		−0.479	0.099	***	0.000	0.103		0.333	0.115	***	−0.275	0.093	***
	basic&applied	b_a	0.359	0.199	*	0.842	0.200	***	0.397	0.227	*	0.004	0.170		0.522	0.213	**
	applied&dev	a_d	0.239	0.130	*	−0.027	0.146		0.119	0.127		0.070	0.146		−0.126	0.140	
	basic&applied	b_d	−0.258	0.221		−0.360	0.312		−0.114	0.308		−0.186	0.277		−0.504	0.390	
	integrated	integrated	−0.058	0.186		0.397	0.157	**	0.193	0.177		0.128	0.186		0.327	0.231	
	service	service	−0.073	0.156		−0.662	0.137	***	−0.319	0.134	**	0.532	0.141	***	−0.273	0.149	*
	oth_stage	oth_stage	−0.363	0.335		−0.809	0.390	**	−0.855	0.349	**	1.065	0.447	**	−0.279	0.333	
Technological Objective of R&D (base:new process	Process improvement	_Iprodproc_2	0.092	0.144		−0.222	0.176		0.066	0.179		−0.195	0.176		0.021	0.186	
	New product	_Iprodproc_3	0.056	0.132		0.091	0.131		0.149	0.128		0.248	0.138	*	0.131	0.142	
	Product improvement	_Iprodproc_4	0.075	0.142		−0.253	0.160		0.164	0.146		0.032	0.143		−0.121	0.159	
	Other	_Iprodproc_5	−0.428	0.465		0.427	0.379		−0.499	0.374		−0.744	0.361	**	0.548	0.414	
Firm characteristics	Sales	lnsales	0.038	0.030		0.113	0.037	***	0.040	0.038		−0.037	0.034		0.095	0.029	***
	RD/sales	rdsales	0.262	0.949		0.513	0.933		−1.613	1.049		−4.859	1.218	***	0.471	0.881	
	Patent stock	ln1uspat	0.065	0.024	***	−0.040	0.033		−0.029	0.029		−0.052	0.031	*	−0.090	0.027	***
control	triadic patent	_Itriadic_1	0.130	0.073	*	0.159	0.076	**	−0.048	0.085		0.160	0.085	*	0.078	0.075	
Firm scale effect	Firm size	lnsales+ln1us	0.104	0.025	***	0.073	0.031	**	0.011	0.031		−0.088	0.034	***	0.006	0.028	
	Note. * significant at 10%, ** significant at 5%, *** significant at 1%																
	Cutoff points, dummies for application years and for US technology classes are not reported.																

Table 4 Team size and man months of inventive labors (Clustering on applicant, single applicant only)

			OLS for lninventors									OLS for lnmonth2								
			Model 1			Model 2			Model 3			Model 4			Model 5			Model 6		
			Number of obs = 3504			Number of obs = 2832			Number of obs = 2832			Number of obs = 3378			Number of obs = 2731			Number of obs = 2731		
			720 clusters			438 clusters			437 clusters			710 clusters			437 clusters			437 clusters		
			R-squared = 0.1347 Root MSE = .5677			R-squared = 0.1444 Root MSE = .57319			R-squared = 0.2684 Root MSE = 1.1769			R-squared = 0.2648 Root MSE = 1.1702			R-squared = 0.2684 Root MSE = 1.1769			R-squared = 0.2689 Root MSE = 1.177		
				Robust			Robust			Robust			Robust			Robust			Robust	
		Variable	Coef.	Std. Err.		Coef.	Std. Err.		Coef.	Std. Err.		Coef.	Std. Err.		Coef.	Std. Err.		Coef.	Std. Err.	
Business Objective of R&D (Base:core)	Non-core	_Iobjectiv~2	0.007	0.035		-0.017	0.037		-0.019	0.036		0.039	0.056		0.026	0.062		0.024	0.062	
	Unknown	_Iobjectiv~3	-0.101	0.045	**	-0.130	0.053	**	-0.132	0.053	**	-0.234	0.100	**	-0.238	0.116	**	-0.239	0.116	**
	New business	_Iobjectiv~4	0.040	0.030		0.036	0.033		0.032	0.033		0.039	0.056		0.055	0.067		0.052	0.067	
	Technology base	_Iobjectiv~5	-0.096	0.039	**	-0.098	0.050	*	-0.098	0.051	*	-0.140	0.082	*	-0.164	0.090	*	-0.162	0.090	*
	Other	_Iobjectiv~6	-0.071	0.116		-0.149	0.147		-0.148	0.148		-0.498	0.228	**	-0.392	0.288		-0.393	0.291	
Scope and stage of research (base: applied)	basic	basic_pure	0.005	0.053		0.031	0.056		0.029	0.057		-0.020	0.107		-0.039	0.113		-0.042	0.113	
	dev	dev_pure	-0.138	0.031	***	-0.115	0.034	***	-0.119	0.034	***	-0.104	0.060	*	-0.122	0.062	*	-0.125	0.062	**
	basic&applied	b_a	0.010	0.065		0.043	0.071		0.037	0.071		-0.034	0.111		-0.009	0.120		-0.012	0.120	
	applied&dev	a_d	-0.135	0.037	***	-0.116	0.042	***	-0.123	0.042	***	0.058	0.079		0.145	0.086	*	0.142	0.086	
	basic&applied	b_d	-0.092	0.079		-0.062	0.091		-0.069	0.091		-0.071	0.196		-0.046	0.233		-0.049	0.235	
	integrated	integrated	-0.107	0.049	**	-0.083	0.053		-0.088	0.053	*	0.064	0.106		0.003	0.120		0.002	0.120	
	service	service	-0.012	0.037		-0.029	0.044		-0.033	0.043		-0.207	0.076	***	-0.241	0.093	***	-0.242	0.093	***
	oth_stage	oth_stage	0.070	0.101		0.119	0.105		0.114	0.105		-0.244	0.154		-0.185	0.192		-0.187	0.191	
Technological Objective of R&D (base:new process	Process improvement	_Iprodproc_2	-0.062	0.055		-0.016	0.067		-0.017	0.066		-0.467	0.099	***	-0.435	0.114	***	-0.436	0.114	***
	New product	_Iprodproc_3	-0.036	0.040		-0.007	0.044		-0.006	0.044		0.031	0.074		0.032	0.081		0.030	0.080	
	Product improvement	_Iprodproc_4	-0.071	0.045		-0.031	0.050		-0.033	0.051		-0.238	0.075	***	-0.257	0.082	***	-0.260	0.082	***
	Other	_Iprodproc_5	-0.187	0.107	*	-0.198	0.115	*	-0.199	0.114	*	-0.475	0.188	**	-0.447	0.234	*	-0.449	0.234	*
Firm characteristics	Sales	lnsales	0.043	0.015	***	0.064	0.019	***	0.049	0.021	**	0.045	0.014	***	0.021	0.021		0.011	0.024	
	RD/sales	rdsales	0.049	0.476		0.387	0.506		0.412	0.544		-0.615	0.634		-0.566	0.733		-0.650	0.719	
	Patent stock	ln1uspat				-0.025	0.011	**	-0.026	0.011	**				0.011	0.016		0.010	0.016	
	HHI of US patents	hhi_pat							-0.271	0.143	*							0.000	0.000	
	Debt asset	debtasset							0.067	0.125								-0.098	0.122	
control	research length	lnres_app										0.644	0.026	***	0.669	0.028	***	0.670	0.028	***
	triadic patent	triadic	0.172	0.022	***	0.181	0.026	***	0.182	0.026	***	0.208	0.041	***	0.183	0.046	***	0.182	0.046	***
	Firm size	lnsales+ln1uspa	0.043	0.015	***	0.039	0.022	*	0.023	0.024		0.045	0.014	***	0.032	0.018	*	0.022	0.022	

Note. * significant at 10%, ** significant at 5%, *** significant at 1%. Cutoff points, dummies for application years and for US technology classes are not reported.

Appendix Table 1. Estimations based on R&D (use of firm level R&D, *ln1rd*, as an independent variable)

			R&D Productivity (1): the number of patents from the project (size_pat)								
			Model 1			Model 2			Model 3		
			Number of obs = 3380			Number of obs = 3381			Number of obs = 2437		
			711 Clusters			712 Clusters			578 Clusters		
			Log pseudolikelihood = −4368.8884 Pseudo R2 =			Log pseudolikelihood = −4344.9469 Pseudo R2 =			Log pseudolikelihood = −2965.1567 Pseudo R2 =		
				Robust			Robust			Robust	
		Variable	Coef.	Std. Err.		Coef.	Std. Err.		Coef.	Std. Err.	
Business Objective of R&D (Base:core)	Non-core	_Iobjectiv~2	−0.125	0.093		−0.135	0.093		−0.509	0.121	***
	Unknown	_Iobjectiv~3	−0.278	0.165	*	−0.290	0.162	*	0.005	0.214	
	New business	_Iobjectiv~4	0.340	0.098	***	0.312	0.098	***	−0.171	0.095	*
	Technology base	_Iobjectiv~5	0.021	0.173		0.001	0.170		−0.198	0.168	
	Other	_Iobjectiv~6	1.057	0.695		1.035	0.702		0.073	0.334	
Scope and stage of research (base: applied)	basic	basic_pure	0.085	0.149		0.083	0.147		−0.115	0.154	
	dev	dev_pure	−0.165	0.126		−0.145	0.124		−0.034	0.115	
	basic&applied	b_a	0.200	0.173		0.174	0.169		0.425	0.211	**
	applied&dev	a_d	0.325	0.133	**	0.346	0.131	***	0.265	0.136	*
	basic&applied	b_d	0.333	0.242		0.329	0.239		0.182	0.289	
	integrated	integrated	0.656	0.175	***	0.696	0.176	***	0.528	0.189	***
	service	service	−0.217	0.121	*	−0.186	0.121		0.013	0.145	
	oth_stage	oth_stage	0.102	0.281		0.155	0.291		0.186	0.427	
Technological Objective of R&D (base:new process	Process improvement	_Iprodproc_2	−0.650	0.182	***	−0.673	0.182	***	−0.578	0.159	***
	New product	_Iprodproc_3	−0.040	0.142		−0.030	0.140		−0.101	0.138	
	Product improvement	_Iprodproc_4	−0.443	0.147	***	−0.427	0.144	***	−0.590	0.154	***
	Other	_Iprodproc_5	−0.601	0.374		−0.607	0.366	*	0.471	0.399	
Firm characteristics	Sales	lnsales				0.182	0.027	***	−0.004	0.028	
	RD/sales	ln1rd	0.068	0.020	***						
	RD	ln1rds				−0.026	0.020		0.036	0.025	
control	research length	lnres_app	0.427	0.045	***	0.427	0.045	***	0.266	0.059	***
	triadic patent	triadic	0.259	0.077	***	0.265	0.075	***	0.574	0.093	***

Note. * significant at 10%, ** significant at 5%, *** significant at 1%. Cutoff points, dummies for application years and for US technology classes are not reported.

Appendix Table 2. Determinants of R&D Performance at project level (use of the focal patent, Clustering on applicant, single applicant only)

	R&D Productivity (3): Internal commercialization (use2)											
	Model 1			Model 2			Model 3			Model 4		
	Number of obs = 3370			Number of obs = 2723			Number of obs = 2639			Number of obs = 2619		
	712 Clusters			437 Clusters			434 Clusters			432 Clusters		
	Log pseudolikelihood = −2115.1383 Pseudo R2 = 0.0938			Log pseudolikelihood = −1702.4083 Pseudo R2 = 0.0980			Log pseudolikelihood = −1627.2149 Pseudo R2 = 0.1104			Log pseudolikelihood = −1606.2739 Pseudo R2 = 0.1152		
	Coef.	Robust Std. Err.		Coef.	Robust Std. Err.		Coef.	Robust Std. Err.		Coef.	Robust Std. Err.	
Non−core	−0.253	0.102	**	−0.331	0.121	***	−0.376	0.123	***	−0.374	0.128	***
Unknown	−0.051	0.183		0.023	0.217		−0.044	0.228		−0.053	0.219	
New business	−0.375	0.113	***	−0.325	0.127	**	−0.335	0.126	***	−0.353	0.127	***
Technology base	−1.542	0.169	***	−1.504	0.184	***	−1.509	0.185	***	−1.496	0.188	***
Other	−0.048	0.503		−0.259	0.548		−0.324	0.554		−0.339	0.583	
basic	−0.599	0.183	***	−0.535	0.200	***	−0.507	0.203	**	−0.515	0.204	**
dev	0.313	0.118	***	0.407	0.122	***	0.392	0.118	***	0.423	0.121	***
basic&applied	−0.271	0.235		−0.269	0.247		−0.204	0.254		−0.199	0.260	
applied&dev	0.166	0.128		0.276	0.143	*	0.294	0.139	**	0.333	0.139	**
basic&applied	−0.039	0.308		0.303	0.338		0.318	0.347		0.353	0.348	
integrated	0.054	0.163		−0.016	0.195		0.056	0.202		0.080	0.200	
service	0.719	0.149	***	0.867	0.177	***	0.759	0.180	***	0.782	0.182	***
oth_stage	0.824	0.313	***	1.118	0.398	***	0.875	0.405	**	0.861	0.409	**
Process improvement	0.127	0.182		0.168	0.203		0.220	0.212		0.285	0.214	
New product	−0.057	0.151		−0.166	0.170		−0.131	0.180		−0.116	0.180	
Product improvement	−0.193	0.153		−0.269	0.175		−0.236	0.183		−0.214	0.185	
Other	−0.774	0.395	**	−0.366	0.457		−0.155	0.443		−0.079	0.445	
patent literature							−0.068	0.035	*	−0.078	0.036	**
scientific literature							−0.083	0.037	**	−0.090	0.037	**
internal							0.009	0.031		0.000	0.032	
vertical							0.123	0.024	***	0.120	0.024	***
research base							0.024	0.031		0.029	0.030	
number of inventors										0.172	0.069	**
man month										0.099	0.041	**
PhD										0.081	0.160	
lnsales	−0.125	0.024	***	−0.084	0.038	**	−0.060	0.039		−0.069	0.039	*
rdsales	0.044	1.025		−0.078	1.263		0.579	1.240		0.392	1.254	
Patent stock				−0.061	0.036	*	−0.068	0.036	*	−0.068	0.037	*
research length	0.115	0.051	**	0.142	0.057	**	0.150	0.061	**	0.069	0.064	
triadic patent	0.600	0.085	***	0.609	0.093	***	0.597	0.095	***	0.575	0.096	***
Firm scale effect	−0.125	0.024	***	−0.145	0.031	***	−0.128	0.032	***	−0.137	0.032	***

Note. * significant at 10%, ** significant at 5%, *** significant at 1%. Cutoff points, dummies for application years and for US technology classes are not reported.

Appendix Table 3. Knowledge inflow for initiation of the project with inventor team size (Clustering on applicant, single applicant only)

			Ordered logit equation for knowledge flow														
			Model 1: cncpt_own			Model 2: cncpt_sci			Model 3: cncpt_pat			Model 4: cncpt_v			Model 5: cncpt_res		
			Number of obs = 2754			Number of obs = 2763			Number of obs = 2768			Number of obs = 2762			Number of obs = 2744		
			435 clusters			435 clusters			434 clusters			435 clusters			434 clusters		
			Log pseudolikelihood = −4002.2582 Pseudo R2 = 0.0179			Log pseudolikelihood = −4037.9244 Pseudo R2 =			Log pseudolikelihood = −4031.7025 Pseudo			Log pseudolikelihood = −4162.1467 Pseudo R2 = 0.0343			Log pseudolikelihood = −3943.5194 Pseudo R2 = 0.0325		
				Robust			Robust			Robust			Robust			Robust	
		Variable	Coef.	Std. Err.		Coef.	Std. Err.		Coef.	Std. Err.		Coef.	Std. Err.		Coef.	Std. Err.	
Business Objective of R&D (Base:core)	Non-core	_Iobjectiv~2	−0.147	0.104		−0.232	0.118	**	−0.189	0.113	*	−0.162	0.114		−0.261	0.108	**
	Unknown	_Iobjectiv~3	−0.096	0.177		−0.189	0.175		−0.442	0.154	***	−0.173	0.164		0.051	0.181	
	New business	_Iobjectiv~4	−0.249	0.090	***	0.147	0.096		0.035	0.085		−0.192	0.090	**	0.228	0.106	**
	Technology base	_Iobjectiv~5	−0.288	0.169	*	0.100	0.181		−0.119	0.170		−0.443	0.166	***	0.029	0.182	
	Other	_Iobjectiv~6	−1.005	0.719		−0.795	0.515		−0.729	0.610		−0.560	0.418		−0.420	0.622	
Scope and stage of research (base: applied)	basic	basic_pure	−0.040	0.149		0.272	0.146	*	0.190	0.145		−0.160	0.138		0.502	0.157	***
	dev	dev_pure	0.176	0.106	*	−0.414	0.100	***	0.068	0.102		0.373	0.114	***	−0.210	0.096	**
	basic&applied	b_a	0.385	0.202	*	0.791	0.198	***	0.345	0.222		0.004	0.169		0.491	0.214	**
	applied&dev	a_d	0.264	0.128	**	0.034	0.148		0.185	0.124		0.108	0.145		−0.067	0.140	
	basic&applied	b_d	−0.238	0.214		−0.287	0.314		−0.019	0.305		−0.149	0.275		−0.447	0.385	
	integrated	integrated	−0.022	0.182		0.424	0.157	***	0.223	0.174		0.154	0.187		0.353	0.232	
	service	service	−0.065	0.152		−0.630	0.138	***	−0.282	0.132	**	0.547	0.143	***	−0.245	0.148	*
	oth_stage	oth_stage	−0.414	0.324		−0.818	0.386	**	−0.875	0.347	**	1.046	0.448	**	−0.274	0.332	
Technological Objective of R&D (base:new process	Process improvement	_Iprodproc_2	0.089	0.146		−0.214	0.179		0.074	0.179		−0.183	0.178		0.036	0.189	
	New product	_Iprodproc_3	0.056	0.131		0.076	0.131		0.137	0.127		0.252	0.139	*	0.133	0.143	
	Product improvement	_Iprodproc_4	0.075	0.138		−0.256	0.160		0.170	0.146		0.041	0.143		−0.110	0.159	
	Other	_Iprodproc_5	−0.317	0.469		0.427	0.377		−0.492	0.387		−0.696	0.364	*	0.562	0.422	
Inventors input	number of inventors	lninventors	0.353	0.064	***	0.280	0.068	***	0.360	0.066	***	0.183	0.053	***	0.176	0.062	***
	PhD	PhD	−0.278	0.120	**	0.489	0.142	***	0.490	0.121	***	0.070	0.133		0.440	0.129	***
Firm characteristics	Sales	lnsales	0.021	0.029		0.091	0.036	**	0.014	0.037		−0.050	0.033		0.082	0.030	***
	RD/sales	rdsales	0.229	0.935		0.201	0.913		−1.920	1.084	*	−4.996	1.208	***	0.170	0.863	
	Patent stock	ln1uspat	0.078	0.025	***	−0.030	0.033		−0.015	0.028		−0.047	0.030		−0.081	0.027	***
control	triadic patent	_Itriadic_1	0.075	0.075		0.118	0.077		−0.103	0.083		0.139	0.086		0.050	0.077	
	Firm size	lnsales+ln1uspat	0.098	0.025	***	0.061	0.031	**	−0.002	0.029		−0.097	0.032	***	0.000	0.028	
	Note. * significant at 10%, ** significant at 5%, *** significant at 1%. Cutoff points, dummies for application years and for US technology classes are not reported.																