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The Race between R&D and ICT: Evidence on Firm Level Impacts on Innovation, Skills and Productivity

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Abstract

Both Research and Development (R&D) and Information and Communication Technology (ICT) investment have been identified as sources of relative innovation underperformance in Europe vis-à-vis the United States. In this paper we investigate R&D and ICT investment at the firm level in an effort to assess their relative importance and to what extent they are complements or substitutes, and also their implications for the skill composition of the workforce. We use data on a large unbalanced panel data sample of Italian manufacturing firms constructed from four consecutive waves of a survey of manufacturing firms together with a version of the CDM model (Crepon *et al.*, 1998) that has been modified to include ICT investment together with R&D as the two main inputs into innovation and productivity. […]

Keywords: R&D, ICT, Innovation, Productivity, Skills, Italy.

JEL classification: L60, O31, O33.

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*1. Introduction**

Both Research and Development (R&D) and Information and Communication Technology (ICT) investment have been identified as areas of relative underperformance in Europe vis-à-vis the United States. For example, Van Ark *et al.* (2003) concluded the following in their study of the reasons for lower productivity growth in Europe: "The results show that U.S. productivity has grown faster than in the EU because of a larger employment share in the ICT producing sector and faster productivity growth in services industries that make intensive use of ICT." [a graph and some aggregate statistics will be added; reference Mairesse and Kocoglu 2005].

Thus the Lisbon agenda calls for increased business R&D intensity in Europe. However, Moncada-Paternò-Castello *et al.* 2009, Hall and Mairesse 2009, and O'Sullivan 2006 all point to the differences in industrial structure, specifically the smaller ICT sector as the main cause of lower R&D intensity in Europe. Although the ICT industry is a global one, one cannot help but wonder how this fact interacts with the apparent lower demand for ICT investment. So it is natural to ask whether ICT investment results in innovation and productivity growth in European firms, and how this kind of investment interacts with R&D investment. There is also considerable policy interest in the implications of these kinds of investments for the skill composition of the workforce. [More discussion of the impact of ICT and R&D on productivity and the relevance of organizational innovation (Bugamelli and Pagano, 2004)]

One might expect that R&D is would be targeted mainly at new and improved product innovation (following the results of much earlier surveys, such as Mansfield's). On the other hand, ICT investment has frequently been found to be accompanied by innovations in processing and the organization of work within the firm (e.g., Greenan *et al.*, 1996). To our knowledge, very few papers have investigated R&D and ICT investment jointly and tried to assess their relative importance and to what extent they

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are complements or substitutes. The little work there is has produced conflicting results. For example, while Cerquera and Klein (2008) find that a more intense use of ICT brings about a reduction in R&D effort, Polder *et al.* (2009) find a complementarity effect on R&D, albeit one that is small in magnitude.

The analysis in this paper is based on a version of the well-known model of R&D, innovation, and productivity that is due to Crepon, Duguet, and Mairesse (1998) to go beyond prior work in this area. We treat ICT in parallel with R&D as an input to innovation rather than simply as an input of the production function. By doing this, we take into account the possible complementarities among innovation activities. In addition we add measures of organizational change and workforce skills to the model to explore the interaction among all these factors. Our analysis examines the firm level relationships between product, process and organizational innovation, skill composition, labor and total productivity, and two of their major determinants, namely R&D and ICT, using data on firms from a single European country, Italy. The evidence is based on a large unbalanced panel data sample of Italian manufacturing firms constructed from the four waves 1995-1997, 1998-2000, 2001-2003 and 2004-2006 of the "Survey on Manufacturing Firms" conducted by Unicredit.

Taking advantage of our previous work (Hall, Lotti and Mairesse 2008 and 2009), and in the spirit of Polder *et al.* (2009), we rely on an extension of a modified version of the CDM model (Griffith and al., 2006) that includes ICT investment together with R&D as two main inputs into innovation and productivity. This extension of the model specification leads to increased difficulties in estimation owing to the increased number of equations with qualitative dependent variables. In this preliminary version of the paper, we bypass these difficulties by estimating the different blocks of the model sequentially, while still correcting for endogeneity and selectivity in firm R&D and ICT investments. We first consider two interrelated investment equations for ICT and R&D (consisting of a bivariate probit for the presence of the two investments and two regressions that predict their levels). Next, we test different sets of (bivariate) probit equations for binary indicators of product and process innovation and of organizational change and skill intensity with the levels of R&D and ICT investments as predictor variables. Finally we estimate the productivity impacts of the different modes of innovation in a production function, controlling for physical capital.

The next section of the paper reviews the micro-econometric evidence on the use of information and communication technology to enhance the productivity of firms. This is followed by a presentation of our model, data and the results of estimation. The final section offers some preliminary conclusions.

2. ICT and productivity: a micro perspective

The earliest studies on the link between ICT and productivity at the macro level were mainly aimed at understanding the so-called Solow Paradox, i.e. the fact that "computers were visible everywhere except in the productivity statistics" (Solow, 1985).

In fact, measuring ICT correctly at the aggregate level is a non-trivial issue. The ideal measure capturing the economic contribution of capital inputs in a production theory context is the flow of capital services, but building this variable from raw data entails non-trivial assumptions regarding the measurement of the investment flows in the different assets and the aggregation over vintages of a given type of asset. Moreover, deflators need to be based on hedonic techniques given the rapid technical change in this sector.

Availability of data at the firm level enables one to overcome some of the aforementioned issues and at the same time to account for heterogeneity. In fact, many studies find an impact on productivity that is greater than that for ordinary non-ICT investment, measuring ICT with alternative proxies, like a measure of the stock of a firm's computer hardware at the establishment level (Brynjolfsson and Hitt 1995, Brynjolfsson and Yang 1998, Brynjolfsson *et al.* 2002), ICT use at the firm level (number of PCs, the use of network, number of employees using ICT; Greenan and Mairesse, 1996) and ICT investment expenditure. The latter measure is clearly desirable, as it provides a direct measure of investment outlay that can be easily used in a production function and we will rely on it in our empirical analysis.

Even if based on different indicators, the relationship between ICT and productivity at the firm level is generally positive (Black and Lynch (2001) and Bresnahan (2002) for the US, Greenan *et al.* (2001) for France, Bugamelli and Pagano (2004) and, more recently, Castiglione (2009) on Italy), but ICT alone is not enough to affect productivity. In fact, Black and Lynch (2001) and Bresnahan (2002) focus on the interaction between ICT, human capital and organizational change. Ignoring these complementarities may lead to overestimating the effect of ICT on productivity. In fact, implementation of ICT projects requires reorganization of the firm around the new technology, but reorganization needs time to be implemented and, more importantly, it implies costs, like retraining of workers, consultants, management time. See also Brynjolfsson *et al.* (2002) on the firm valuation effects of information technology acquisition, which they show to be partly proxying for the costs of the organizational change that accompanies such acquisition.

Therefore, we treat ICT as an input, both of the production function and, more importantly, of the knowledge production function. In the first case, we reconcile with a more traditional view: ICT enables "organizational" investments, mainly business processes and new work practices which, in turns, lead to cost reductions and improved output and, hence, productivity gains. In a less traditional view, ICT is an input for producing new goods and services (like internet banking), new ways of doing business (B2B) and new ways of producing goods and services (integrated management). Consequently, in our modeling framework we treat ICT as a pervasive input rather than an input of the production function only. By doing so, we take explicitly into account possible complementarities with innovation activity, mainly R&D but also organizational innovation and human capital.

To do this, we incorporate ICT expenditure in a structural model based on the "CDM" framework (Crépon-Duguet-Mairesse, 1998). Crépon, Duguet and Mairesse (1998) propose a model that establishes a relationship among innovation input, innovation output and productivity. The structural model allows a closer look at the black box of the innovation process at the firm level: it not only analyzes the relationship between innovation input and productivity, but it also sheds some light on the process in between the two. The CDM approach is based on a three-step model following the logic of firms' decisions and outcomes in terms of innovation. In the first step, firms decide whether to engage in R&D or not and the amount of resources to invest. Given the firm's decision to invest in innovation, the second step is characterized by a knowledge production function (as in Pakes and Griliches, 1984) in which innovation output stems from innovation input and other input factors. In the third step, an innovation augmented Cobb-Douglas production function describes the effect of innovative output on the firm's productivity.

We extend the CDM model to include an equation for ICT as an enabler of innovation and organizational innovation as an indicator of innovation output, as in Polder *et al.* (2009), and we add an indicator of skill intensity. Using data from different sources (mainly surveys) at the Statistics Netherlands on firms belonging to the manufacturing and services industries, Polder *et al.* find that ICT is an important driver of innovation. While doing more R&D has a positive effect on product innovation in manufacturing only, they find positive effects of product and process innovation when combined with organizational innovation in both sectors.

3. The extended CDM model

3.1. The input decision

In this first stage, we treat the decision to invest in R&D and/or in ICT symmetrically. A firm must decide whether to invest or not, then, given that the firm chooses to invest, it must choose the investment intensity. This statement of the problem can be modeled with a standard sample selection model. We use X to denote either R&D or ICT investment, and define the model as follows:

$$DX_i = \begin{cases} 1 & if \quad DX_i^* = w_i\alpha + \varepsilon_i > \overline{c} \\ 0 & if \quad DX_i^* = w_i\alpha + \varepsilon_i \le \overline{c} \end{cases} \tag{1}$$

DX_i is an (observable) indicator function that takes value 1 if firm i has (or reports) positive expenditures on X, DX_i^* is a latent indicator variable such that firm i decides to perform (or to report) expenditures if it is above a given threshold $\overline{c}$, w_i is a set of explanatory variables affecting the decision, and ε_i is the error term. For those firms doing R&D or investing in ICT, we observe the amount of resources devoted to these activities:

$$X_i = \begin{cases} X_i^* = z_i\beta + e_i & if \quad DX_i = 1 \\ 0 & if \quad DX_i = 0 \end{cases} \tag{2}$$

where X_i* is the unobserved latent variable corresponding to the firm's investment, and z_i is a set of determinants of the expenditure intensity. Assuming that the error terms in (1) and (2) are bivariate normal with zero mean and covariance matrix given by

$$\begin{pmatrix} 1 & \\ \rho\sigma_{\varepsilon} & \sigma_{\varepsilon}^{2} \end{pmatrix} \tag{3}$$

the system of equations (1) and (2) can be estimated by maximum likelihood. In the literature, this model is sometimes referred to as a Heckman selection model (Heckman, 1979) or Tobit type II model (Amemiya, 1984).

Before estimating the selection models, we performed a non parametric test for the presence of selection bias, for both the R&D and ICT intensity equations (see Das, Newey and Vella, 2003, and Vella, 1998 for a survey). In so doing, we first estimate a probit model in which the presence of positive R&D (ICT) expenditures is regressed on a set of firm characteristics: firm size, age and their squares, a set of dummies indicating competitors' size and location, dummy variables indicating (i) whether the firm received government subsidies, and (ii) whether the firm belongs to an industrial group; the results are reported in Table A1 [not included in this version of the paper] in the appendix. From this estimate, for each firm we recover the predicted probability of having R&D (ICT) and the corresponding Mills' ratio. Then we estimate a simple linear (OLS) for R&D (ICT) intensity, adding to this equation the predicted probabilities from the R&D (ICT) decision equation, the Mills' ratio, their squares and interaction terms. The presence of selectivity bias is then tested for by looking at the significance of those "probability terms".[1] As one can see in this table, the probability terms are never significant, either singly or jointly. Therefore we adopted a simple OLS model for the R&D (ICT) intensity decision since it appears that there is no selectivity bias. The results are reported in the first columns of Tables 3 for R&D and 4 for ICT respectively: estimates are performed using the pooled sample, including in the

[1] Note that this is a generalization of Heckman's two step procedure for estimation when the error terms in the two equations are jointly normally distributed. The test here is valid even if the distribution is not normal.

regression time, 2-digit industry and "wave dummies" as controls. Wave dummies are a set of indicators for the firm's presence or absence in the three waves of the survey.[2]

3.2. Innovation outcomes and skill composition choice

In the second step, we estimate a knowledge production function but, as in the original CDM model, in order to account for that part of innovation activity that has not been formalized, we do not restrict estimation to R&D or ICT performing firms only. This is likely to be especially important for SMEs, which represent nearly 90% of our sample. The outcomes of the knowledge production function are product and process innovation:

$$\begin{cases} PROD_i = X_i^*\gamma_1 + x_i\delta_1 + u_{1i} \\ PROC_i = X_i^*\gamma_2 + x_i\delta_2 + u_{2i} \end{cases}, \tag{4}$$

where $X_i* = RD_i*$ or ICT_i* is the latent innovation effort, which is proxied by the predicted value of R&D or ICT intensity from the model in the first step, x_i is a set of covariates and u_{1i} and u_{2i} are the error terms such that $Cov(u_{1i}, u_{2i}) = \rho_u$. We argue that including the predicted R&D or ICT intensity in the regression accounts for the fact that all firms may have some kind of innovative effort, but only a few of them report it (Griffith *et al.*, 2006). Moreover, using the predicted value instead of the realized value is a sensible way to instrument the innovative effort in the knowledge production function in order to deal with simultaneity problem between the R&D or ICT effort and the expectation of innovative success.

Equation (3) is estimated as a bivariate probit model, assuming that most of the firm characteristics which affect product and process innovation are the same, although of course their impact may differ. The only exception is the ordinary investment rate, which is assumed to be related to process innovation but not to product innovation. In this version of the paper we estimate equation (3) using either R&D or ICT as the

[2] For example, a firm present in all the four waves will have a "1111" code, "1000" if present in the first only, "1100" if in the first and in the second only, and so forth. These codes are transformed into a set of six dummies ($2^4 = 16$ minus the 0000 case and the exclusion restriction).

driver of innovation, due to the high collinearity between the predicted values for these two variables. In subsequent work we hope to include both variables by adding additional instruments to the first step.

In order to examine the roles of organizational change and skill intensity, we estimate two more bivariate probits: one where the presence of organizational change associated to product and to process innovation are the dependent variables, while in the other the presence of high skill intensity and organizational change for product innovations are the relevant outcomes.

3.3. The productivity equation

In the third and final step of the model, production is modeled using a simple Cobb-Douglas technology with labor, capital, and knowledge inputs:

$$y_i = \pi_1 k_i + \pi_2 PROD_i^* + \pi_3 PROC_i^* + Z_i \psi + \nu_i \tag{5}$$

Where *y* is labor productivity (sales per employee, in logs), *k* is the log of capital per worker, *PROD** and *PROC** are the knowledge inputs, proxied by the predicted probabilities of innovation from the previous step, and the *Z* are a set of controls

including size, age, year, industry, and wave effects. Organizational change and skill intensity may also be included in this equation, depending on the specification adopted on the previous steps. In order to address the possible endogeneity issue concerning the knowledge inputs, we use their predicted probabilities.

[This section will have more discussion of the modeling choices and identification issues in the next version].

4. Data and descriptive statistics

We use firm level data from the 7^{th}, 8^{th}, 9^{th} and 10^{th} waves of the "Survey on Manufacturing Firms" conducted by Unicredit (an Italian commercial bank, formerly known as Medicredito-Capitalia). These four surveys were carried out in 1998, 2001, 2004 and 2007 respectively, using questionnaires administered to a representative sample of Italian manufacturing firms. Each survey covered the three years immediately prior (1995-1997, 1998-2000, 2001-2003, 2004-2006) and although the survey questionnaires were not identical in all four of the surveys, they were very similar in the sections used in this work. All firms with more than 500 employees were included, whereas smaller firms were selected using a sampling design stratified by geographical area, industry, and firm size. We merged the data from these three surveys, excluding firms with incomplete information or with extreme observations for the variables of interest.[3]

Our final sample is an unbalanced panel of 13,521 observations on 9,341 firms, of which only 560 are present in all four waves. Table 1 contains some descriptive statistics for the unbalanced panel. Not surprisingly, the firm size distribution is skewed to the right, with an average of around 118 employees, but with a median of 36 onl; for the 560 firms that are present in all four years, the average size is 249 employees with a median of 72. In our sample, 64% of the firms engage in traditional innovation activity on average, but only 42% invest in R&D, with an average of almost 4 thousand euros per employee. While nearly 70% of the firms in the sample invest in ICT, the intensity is much lower if compared to R&D, one thousand euros per employee.

Turning to the variables we will use to instrument the R&D and ICT investment choices, 42% of the firms in the sample report that they have national competitors, while 18% and 14% have European and international competitors, respectively. 26% of the firms belong to an industrial group. Interestingly, 42% of the firms in our sample received a subsidy of some kind (mainly for investment and R&D). Only one third of the sample consists of firms in high-tech industries, reflecting the traditional sector orientation of Italian industry.

In Table 2 we look at some of the innovation indicators more closely. A firm that invests in R&D is also slightly more likely to invest in ICT (compare 42%*69% = 29% to 33%). For 28% of the firms product and process innovations go together, while 24%

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[3] We require that sales per employee be between 2000 and 10 million euros, growth rates of employment and sales of old and new products between -150 per cent and 150 per cent, and R&D employment share less than 100 per cent. We also replaced R&D employment share with the R&D to sales ratio for the few observations where it was missing. For further details, see Hall, Lotti and Mairesse (2008). In addition, we restrict the sample by excluding the very few observations with missing investment.

are process innovators only. In the last panel of Table 2 we show the distribution of the various combinations of innovation activities. There are $2^4 = 16$ possible combinations but only 6 account for almost 90 per cent of the observations: No innovation (31%), only process innovation (15%), product and process together (15%), all (9%), only product (9%), and process combined with organizational innovation related to process (8%). In general, process innovation is more likely than product innovation for these firms.

Table 2 also shows that there is some association between innovation and both doing R&D and investing in ICT, although the association is stronger for R&D. In addition, the probability of product innovation increases more than that for process innovation if the firm is an R&D-doer, whereas the opposite is true for ICT investment.

5. *Results and discussion*

We estimate several specifications of the augmented CDM model: in the first two we evaluate the relationship between R&D or ICT intensity and innovation, in the third and the fourth the link between R&D or ICT intensity and organizational change, while in the last one the relationship between ICT intensity, skill intensity and organizational change.

In the first column of Tables 3-7, the input decision is reported. The outcome variables are, alternatively, R&D and ICT intensities, while the covariates are a set of dummy variables that represent size class, the age of the firm, the extent of competition, whether firms received a subsidy and whether they part of a group.

R&D intensity is negatively correlated to firm size, meaning that, conditional on investing in R&D, smaller firms exhibit a higher investment per employee. For ICT, the relationship between investment intensity and firm size is less clear-cut: while medium sized firms tend to invest less per employee than smaller firms (the reference group), larger firms invest the same amount per employee as small firms. International competition (EU and extra EU) is strongly positively related to R&D effort: engaging in exporting activity implies being more specialized in the products and investing more in R&D (see Baldwin, Beckstead, and Caves, 2002, and Baldwin and Gu, 2004). On the contrary, international competition does not affect ICT investment intensity, suggesting that ICT is more an organizational aspect than a strategic one. We find no significant effect of firm's age on R&D or ICT intensities.

Having received a subsidy positively affect R&D effort, but has no impact on ICT, while being part of a group has a positive and significant impact on both R&D and ICT intensities, higher for the latter.

Turning to the second block of our modified CDM model (second column of Table 3 and 4), and to the impact of firm's characteristics and decisions on traditional innovation, we find that size has a positive effect on the likelihood of having process and product innovation. R&D and ICT intensities have a strong, positive effect on the probability of introducing innovation, more intense for product innovation.

R&D and ICT have also a positive impact on the likelihood of introducing organizational change; the effect is higher for ICT, in particular and not surprisingly, for the organizational change associated with new processes (second column of Table 5 and 6). Also, firm size affects the probability of having both kinds of organizational innovation, in a non monotonic fashion. In the last specification (second column of Table 7) we look at the probability of having a high skill intensity (a dummy equal to 1 if the firm has a share of white collars higher than the sectorial average) and organizational change after introduction of a new product. While the impact of firm size on the skill composition is not so clear-cut, it is positive for organizational change after product innovation. Interestingly, ICT intensity has a positive and sizeable impact on skill composition, suggesting the existence of some complementarity between human capital and the adoption of new technologies.

In the last part of the analysis (the last column of Tables 3 and 4), we look at the effect of firm size and of the predicted probabilities of having process innovation only, product innovation only and both kind of innovation together (from the bivatiate probits) on labor productivity. Both specifications (with predicted R&D and ICT intensities) yield similar results: process innovation alone has a negative impact on productivity, while product innovation a positive one, higher when innovation is predicted with ICT. Interestingly, the predicted probabilities of having organizational change associated with product process has a sizeable positive effect on productivity, also when it is associated to organizational change after process innovation. Looking at the last specification (Table 7) it turns out that firm size has virtually no effect on productivity, like in the previous tables. The probability of having a high skill intensity has the greatest (and significant) effect on labor productivity.

6. Conclusions

……to be written…..

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Appendix

Variable Definitions

R&D engagement: dummy variable that takes value 1 if the firm has positive R&D expenditures over the three year of each wave of the survey.

R&D intensity: R&D expenditures per employee, in real terms and in logs.

Process innovation: dummy variable that takes value 1 if the firm declares to have introduced a process innovation during the three years of the survey.

Product innovation: dummy variable that takes value 1 if the firm declares to have introduced a product innovation during the three years of the survey.

Innovator: dummy variable that takes value 1 if the firm has process or product innovation.

Share of sales with new products: percentage of the sales in the last year of the survey coming from new or significantly improved products (in percentage).

Labor productivity: real sales per employee, in logs.

Investment intensity: investment in machinery per employee, in logs.

Public support: dummy variable that takes value 1 if the firm has received a subsidy during the three years of the survey.

Regional – National – European –International (non EU) competitors: dummy variables to indicate the location of the firm’s competitors.

Large competitors: dummy variable that takes value 1 if the firm declares to have large firms as competitors.

Employees: number of employees, headcount.

Age: firm’s age (in years).

Size classes: [11-20], [21-50], [51-250] employees.

Age classes: [<15], [15-25], [>25] years.

Industry dummies: a set of indicators for a 2-digits industry classification.

Time dummies: a set of indicators for the year of the survey.

Wave dummies: a set of indicators for firm's presence or absence in the three waves of the survey

High-tech firms: encompasses high and medium-high technology industries (chemicals; office accounting & computer machinery; radio, TV & telecommunication instruments; medical, precision & optical instruments; electrical machinery and apparatus, n.e.c.; machinery & equipment; railroad & transport equipment, n.e.c.).

Low-tech firms: encompasses low and medium-low technology industries (rubber & plastic products; coke, refined petroleum products; other non-metallic mineral products; basic metals and fabricated metal products; manufacturing n.e.c.; wood, pulp & paper; food, beverages & tobacco products; textile, textile products, leather & footwear).

Table 1 – Descriptive statistics, unbalanced sample

Period: 1995-2006			
Num. of observations (firms)	13,251 (9,341)	Firms with large firms as competitors	39.4%
N. of employees (mean/median)	119/ 36	Firms with regional competitors	15.6%
Age (mean/median)	27/ 23	Firms with national competitors	42.0%
		Firms with EU competitors	17.7%
Firms with nonzero non-ICT investment	91.2%	Firms with international competitors	14.3%
Firms with nonzero R&D	42.0%	Firms within a group	25.5%
Firms with nonzero ICT	68.9%	Firms subsidies' recipients	42.0%
		Firms in the high-tech industries	31.3%
Average non-ICT investment intensity for firms investing*	8.57	Firms in the low-tech industries	68.7%
Average R&D intensity for R&D-doers*	3.92	Firms with product innovation	40.2%
Average ICT intensity for ICT investors*	1.05	Firms with process innovation	51.9%
Average capital intensity*	61.67	Firms with both product and process innovation	27.8%
Labor productivity*	224.69	Firms with organizational innovation for product innovation	15.5%
		Firms with organizational innovation for process innovation	24.6%
		Firms with high skill intensity	38.6%

*Units are real thousands of euros (base year=2000) per employee.

Table 2 – Innovation relationships across firms

		Investing in ICT	
		No	*Yes*
	No	22.2%	35.8%
Doing R&D	*Yes*	8.9%	33.1%

		Product innovation			Organizational change for process innovation	
		No	*Yes*		*No*	*Yes*
	No	35.7%	12.4%	*No*	43.6%	4.5%
Process innovation	*Yes*	24.1%	27.9%	*Yes*	31.8%	20.1%
Organizational change for product innovation	*No*	57.8%	2.0%	*No*	70.4%	5.0%
	Yes	26.7%	13.5%	*Yes*	14.1%	10.5%

Patterns of innovation

Innovation dummy patterns	Obs	Share	Cum share	R&D-doers	ICT-investors
None	4,143	31.3%	31.3%	14.4%	27.7%
Process only	2,023	15.3%	46.6%	12.6%	15.5%
Product and process	2,003	15.1%	61.7%	19.7%	14.6%
All (prod/proc/org)	1,225	9.3%	71.0%	16.0%	11.1%
Product only	1,150	8.7%	79.6%	11.6%	7.8%
Process and Org/process	1,081	8.2%	87.8%	9.4%	9.6%
Org/process only	404	3.1%	90.9%	2.8%	3.3%
Product and Org/product	386	2.9%	93.8%	4.7%	3.3%
Product/process and Org/process	321	2.4%	96.2%	3.8%	3.2%
Product/process and Org/product	138	1.0%	97.2%	1.8%	1.0%
Org/product only	92	0.7%	97.9%	0.7%	0.6%
Org/product and process	91	0.7%	98.6%	0.6%	0.8%
Product and Org/process	63	0.5%	99.1%	0.7%	0.6%
Process and Org/product	44	0.3%	99.4%	0.3%	0.4%
Process and Org/product and process	40	0.3%	99.7%	0.4%	0.4%
Product and Org/product and process	36	0.3%	100.0%	0.5%	0.3%
Total	**13,240**			100.0%	100.0%
Any product innovation	5,589	42.2%		60.9%	44.0%
Any process innovation	7,469	56.4%		68.5%	60.7%
Org. change and prod/proc	3,334	25.2%		37.6%	29.8%

Table 3 - R&D intensity and innovation

Dependent variable	Log R&D per employee	Innovation Process	Innovation Product	Labor productivity
Probability of process inno only				-0.816*** (0.178)
Probability of product inno only				0.694*** (0.251)
Probability of innov, both proc and prod				0.012 (0.102)
Log (capital per employee)				0.185*** (0.008)
R&D intensity (in logs)		0.529*** [0.210] (0.045)	0.758*** [0.292] (0.045)	
Investment per employee (in logs)		0.085*** [0.033] (0.006)		
Size class (21-50 empl.)	-0.344*** (0.091)	0.275*** [0.109] (0.032)	0.361*** [0.140] (0.033)	-0.116*** (0.016)
Size class (51-250 empl.)	-0.285*** (0.093)	0.401*** [0.157] (0.033)	0.473*** [0.184] (0.034)	-0.188*** (0.023)
Size class (251-499 empl.)	-0.270** (0.132)	0.443*** [0.170] (0.057)	0.506*** [0.199] (0.055)	-0.064* (0.036)
Size class (500+ empl.)	-0.220 (0.145)	0.590*** [0.221] (0.062)	0.555*** [0.219] (0.064)	0.075 (0.047)
Age class (15-25 yrs)	-0.027 (0.081)	0.022 [0.009] (0.030)	0.051* [0.020] (0.031)	-0.007 (0.016)
Age class (>25 yrs)	-0.075 (0.073)	0.033 [0.013] (0.029)	0.158*** [0.068] (0.030)	-0.049*** (0.017)
D(Large firm competitors)	0.041 (0.061)			
D(Regional competitors)	0.010 (0.131)			
D(National competitors)	0.074 (0.113)			
D(European competitors)	0.369*** (0.120)			
D(International competitors)	0.518*** (0.125)			
D(Received subsidies)	0.327*** (0.059)			
D(Member of a group)	0.139** (0.070)			
Standard error	2.062	--	--	0.633
Correlation coefficient	--	0.499*** (0.016)		--
R-squared	0.142			0.240
Number of observations	5568	13251		13251

Coefficients and their standard errors are shown. The standard errors are robust to heteroskedasticity and clustered at the firm level.
* = significant at 10%, ** = significant at 5%, *** = significant at 1% .

Industry, wave, and time dummies are included in all equations.
Reference groups: D(provincial competitors), Size class (11-50 empl), Age class (<15 yrs).

Table 4 - ICT intensity and innovation

Dependent variable	Log ICT Inv per employee	Innovation Process	Innovation Product	Labor productivity
Probability of process inno only				-0.848*** (0.190)
Probability of product inno only				1.568*** (0.284)
Probability of innov, both proc and prod				1.096*** (0.208)
Log (capital per employee)				0.182*** (0.008)
ICT intensity (in logs)		0.479*** [0.191] (0.093)	1.157*** [0.445] (0.133)	
Investment per employee (in logs)		0.088*** [0.034] (0.006)		
Size class (21-50 empl.)	-0.137*** (0.035)	0.188*** [0.075] (0.031)	0.288*** [0.112] (0.034)	-0.171*** (0.019)
Size class (51-250 empl.)	-0.209*** (0.041)	0.424*** [0.166] (0.034)	0.555*** [0.216] (0.038)	-0.335*** (0.034)
Size class (251-499 empl.)	-0.179*** (0.064)	0.463*** [0.177] (0.056)	0.545*** [0.215] (0.055)	-0.262*** (0.049)
Size class (500+ empl.)	0.005 (0.090)	0.553*** [0.208] (0.063)	0.426*** [0.168] (0.067)	-0.175*** (0.066)
Age class (15-25 yrs)	-0.031 (0.034)	0.035 [0.014] (0.030)	0.082*** [0.032] (0.031)	-0.019 (0.016)
Age class (>25 yrs)	0.007 (0.033)	0.006 [0.002] (0.028)	0.109*** [0.042] (0.030)	-0.085*** (0.018)
D(Large firm competitors)	0.005 (0.028)			
D(Regional competitors)	-0.029 (0.057)			
D(National competitors)	0.013 (0.050)			
D(European competitors)	0.086 (0.056)			
D(International competitors)	0.085 (0.059)			
D(Received subsidies)	0.031 (0.027)			
D(Member of a group)	0.182*** (0.035)			
Standard error	1.204	--	--	0.631
Correlation coefficient	--	0.470*** (0.013)		--
R-squared	0.047			0.245
Number of observations	9136	13251		13251

Coefficients and their standard errors are shown. The standard errors are robust to heteroskedasticity and clustered at the firm level.
* = significant at 10%, ** = significant at 5%, *** = significant at 1% .

Industry, wave, and time dummies are included in all equations.
Reference groups: D(provincial competitors), Size class (11-50 empl), Age class (<15 yrs).

Table 5 - R&D intensity and organizational change

Dependent variable	Log R&D per employee	Organizational Innovation assoc w new proc	Organizational Innovation assoc w new prod	Labor productivity
Predicted probability of org process inno only				-0.981*** (0.314)
Predicted probability of org product inno only				0.979 (0.669)
Predicted probability of org innov, both proc and prod				0.506** (0.246)
Log (capital per employee)				0.176*** (0.008)
R&D intensity (in logs)		0.599*** [0.183] (0.048)	0.642*** [0.144] (0.051)	
Investment per employee (in logs)		0.041*** [0.013] (0.007)		
Size class (21-50 empl.)	-0.344*** (0.091)	0.337*** [0.107] (0.036)	0.348*** [0.082] (0.041)	-0.111*** (0.017)
Size class (51-250 empl.)	-0.285*** (0.093)	0.446*** [0.145] (0.036)	0.427*** [0.105] (0.041)	-0.173*** (0.024)
Size class (251-499 empl.)	-0.270** (0.132)	0.452*** [0.156] (0.057)	0.533*** [0.149] (0.061)	-0.085** (0.037)
Size class (500+ empl.)	-0.220 (0.145)	0.516*** [0.181] (0.062)	0.499*** [0.139] (0.066)	0.066 (0.046)
Age class (15-25 yrs)	-0.027 (0.081)	0.049 [0.015] (0.033)	0.103*** [0.024] (0.037)	-0.014 (0.016)
Age class (>25 yrs)	-0.075 (0.073)	0.081*** [0.025] (0.031)	0.106*** [0.024] (0.035)	-0.024 (0.016)
D(Large firm competitors)	0.041 (0.061)			
D(Regional competitors)	0.010 (0.131)			
D(National competitors)	0.074 (0.113)			
D(European competitors)	0.369*** (0.120)			
D(International competitors)	0.518*** (0.125)			
D(Received subsidies)	0.327*** (0.059)			
D(Member of a group)	0.139** (0.070)			
Standard error	2.062	--	--	0.567
Correlation coefficient	--	0.835*** (0.022)		--
R-squared	0.142			0.246
Number of observations	5568	13251		10203
Log likelihood				

Coefficients and their standard errors are shown. The standard errors are robust to heteroskedasticity and clustered at the firm level.
* = significant at 10%, ** = significant at 5%, *** = significant at 1% .

Industry, wave, and time dummies are included in all equations.
Reference groups: D(provincial competitors), Size class (11-50 empl), Age class (<15 yrs).

Table 6 - ICT intensity and organizational change

Dependent variable	Log ICT Inv per employee	Organizational Innovation assoc w new proc	Organizational Innovation assoc w new prod	Labor productivity
Predicted probability of org process inno only				-0.486 (0.355)
Predicted probability of org product inno only				2.680*** (0.765)
Predicted probability of org innov, both proc and prod				1.829*** (0.324)
Log (capital per employee)				0.171*** (0.008)
ICT intensity (in logs)		1.185*** [0.364] (0.142)	1.091*** [0.247] (0.153)	
Investment per employee (in logs)		0.045*** [0.014] (0.007)		
Size class (21-50 empl.)	-0.137*** (0.035)	0.310*** [0.098] (0.037)	0.300*** [0.071] (0.042)	-0.167*** (0.018)
Size class (51-250 empl.)	-0.209*** (0.041)	0.545*** [0.179] (0.041)	0.510*** [0.128] (0.046)	-0.304*** (0.029)
Size class (251-499 empl.)	-0.179*** (0.064)	0.490*** [0.171] (0.057)	0.572*** [0.164] (0.061)	-0.288*** (0.046)
Size class (500+ empl.)	0.005 (0.090)	0.371*** [0.126] (0.067)	0.380*** [0.102] (0.071)	-0.161*** (0.058)
Age class (15-25 yrs)	-0.031 (0.034)	0.084** [0.026] (0.033)	0.133*** [0.031] (0.037)	-0.041** (0.017)
Age class (>25 yrs)	0.007 (0.033)	0.043 [0.013] (0.031)	0.065* [0.015] (0.035)	-0.043*** (0.016)
D(Large firm competitors)	0.005 (0.028)			
D(Regional competitors)	-0.029 (0.057)			
D(National competitors)	0.013 (0.050)			
D(European competitors)	0.086 (0.056)			
D(International competitors)	0.085 (0.059)			
D(Received subsidies)	0.031 (0.027)			
D(Member of a group)	0.182*** (0.035)			
Standard error	1.204	--	--	0.633
Correlation coefficient	--	0.843*** (0.022)		--
R-squared	0.047			0.254
Number of observations	9136	13251		13251
Log likelihood				

Coefficients and their standard errors are shown. The standard errors are robust to heteroskedasticity and clustered at the firm level.
* = significant at 10%, ** = significant at 5%, *** = significant at 1% .

Industry, wave, and time dummies are included in all equations.
Reference groups: D(provincial competitors), Size class (11-50 empl), Age class (<15 yrs).

Table 7 - ICT intensity, skill intensity, and organizational change

Dependent variable	Log ICT Inv per employee	D (share of WC higher than sector average)	Org. innovation assoc w new prod	Labor productivity
Predicted probability of upskill only				1.528*** (0.194)
Predicted probability of org. prod innovation				0.352 (0.675)
Log (capital per employee)				0.252 (0.351)
ICT intensity (in logs)		1.701*** [0.648] (0.143)	1.101*** [0.249] (0.153)	0.180*** (0.007)
Investment per employee (in logs)		-0.044*** [-0.017] (0.007)		
Size class (21-50 empl.)	-0.137*** (0.035)	-0.003 [-0.001] (0.037)	0.295*** [0.070] (0.043)	-0.006 (0.028)
Size class (51-250 empl.)	-0.209*** (0.041)	0.099** [0.038] (0.042)	0.513*** [0.129] (0.046)	-0.080* (0.044)
Size class (251-499 empl.)	-0.179*** (0.064)	0.083 [0.032] (0.061)	0.585*** [0.168] (0.060)	-0.003 (0.063)
Size class (500+ empl.)	0.005 (0.090)	-0.295*** [-0.106] (0.073)	0.397*** [0.107] (0.070)	0.140* (0.076)
Age class (15-25 yrs)	-0.031 (0.034)	0.056* [0.021] (0.033)	0.133*** [0.031] (0.038)	0.009 (0.018)
Age class (>25 yrs)	0.007 (0.033)	0.052* [0.020] (0.031)	0.067* [0.015] (0.035)	-0.037** (0.017)
D(Large firm competitors)	0.005 (0.028)			
D(Regional competitors)	-0.029 (0.057)			
D(National competitors)	0.013 (0.050)			
D(European competitors)	0.086 (0.056)			
D(Int'l competitors)	0.085 (0.059)			
D(Received subsidies)	0.031 (0.027)			
D(Member of a group)	0.182*** (0.035)			
Standard error	1.204	--	--	0.631
Correlation coefficient	--	0.075*** (0.018)		--
R-squared	0.047			0.245
Number of observations	9136	13251		13251
Log likelihood				

Coefficients and their standard errors are shown. The standard errors are robust to heteroskedasticity and clustered at the firm level.
* = significant at 10%, ** = significant at 5%, *** = significant at 1% .

Industry, wave, and time dummies are included in all equations.
Reference groups: D(provincial competitors), Size class (11-50 empl), Age class (<15 yrs).